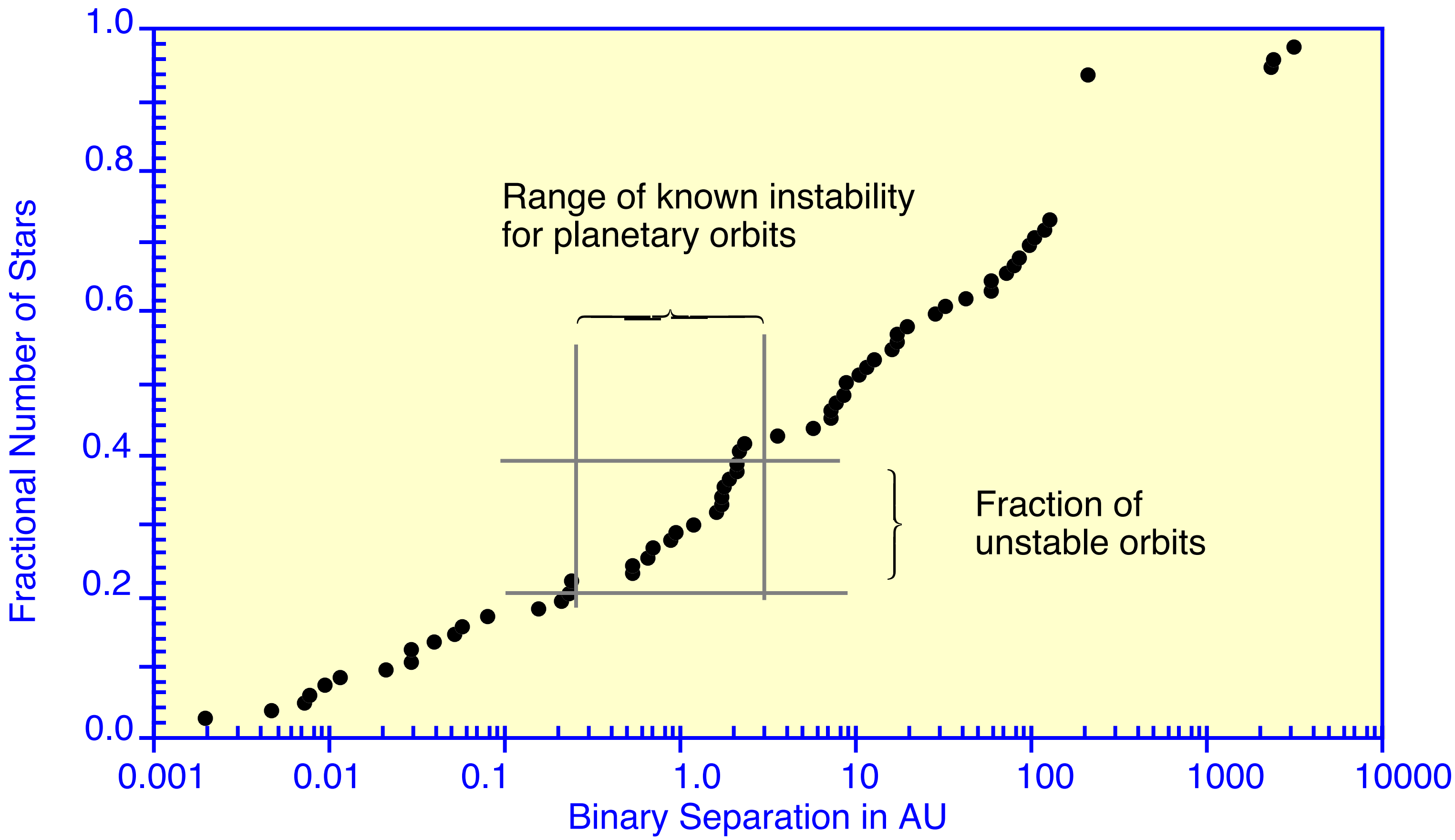
# ASTROPHYSICAL VALUE OF PHOTOMETRY WITH *KEPLER MISSION*

| Stellar Physics | Value |
| --- | --- |
| Stellar rotation rates | Extensive data set |
| p-mode oscillations | Window to stellar interior: Mass, age, He abundance |
| Characteristics of solar-type stars | Define: What is a "normal" star? |
| Frequency of Maunder minimums | Earth climatic implications, paleoclimatology |
| Stellar activity | Star spot cycles, white light flaring |

| Astrophysics | Value |
| --- | --- |
| Cataclysmic Variables | Pre-outburst activity, mass transfer |
| Eclipsing binaries | Frequency of high-mass-ratio systems |
| Active Galactic Nuclei variability | "Engine" size in BL Lac, quasars, blazars |

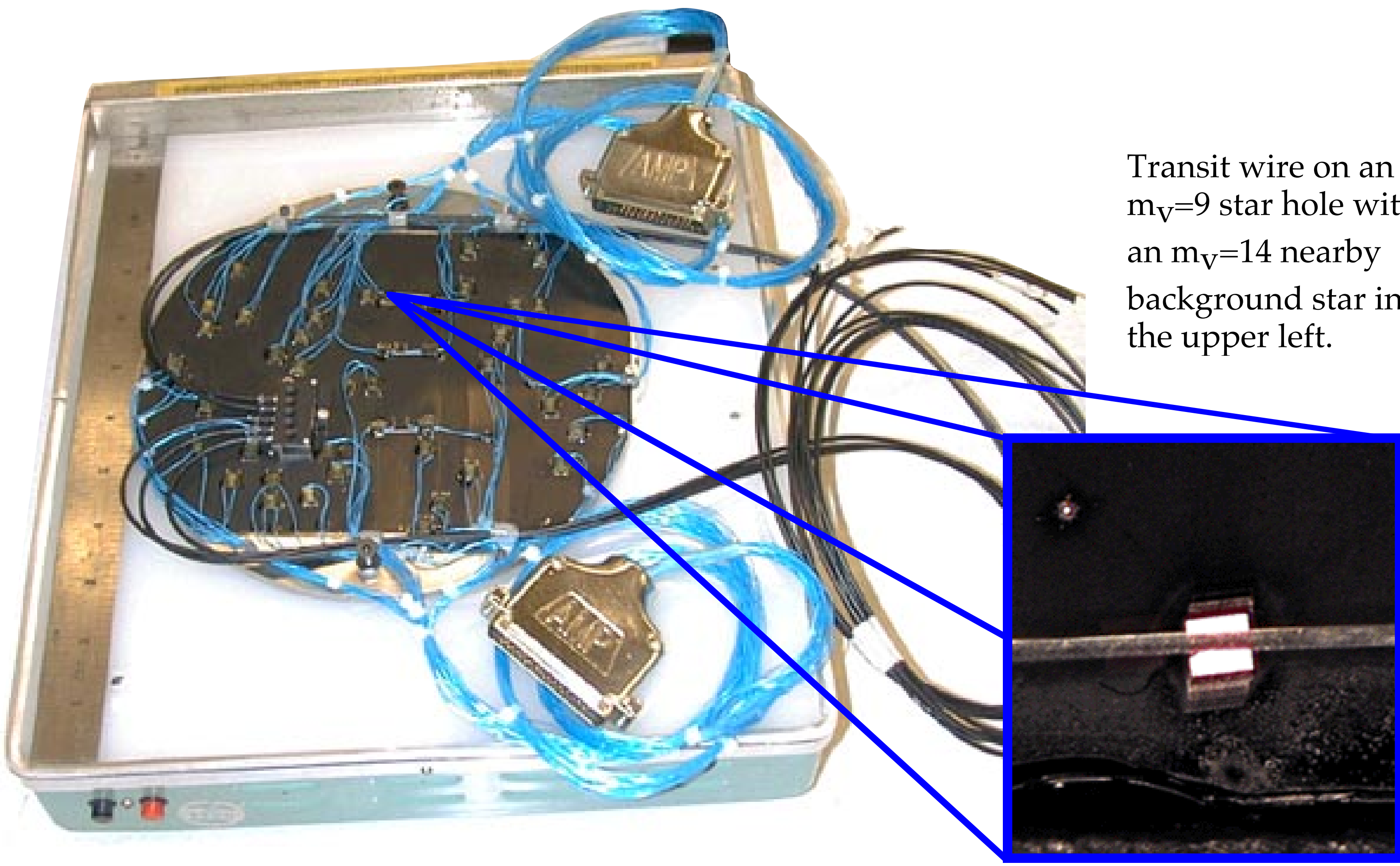
(Ref: NASA CP-10148, "Astrophysical Science with a Spaceborne Photometric Telescope")

# DISTRIBUTION OF BINARY STAR SEPARATIONS




(Heacox and Gathright, *Astron. J.*, Sept 1994)

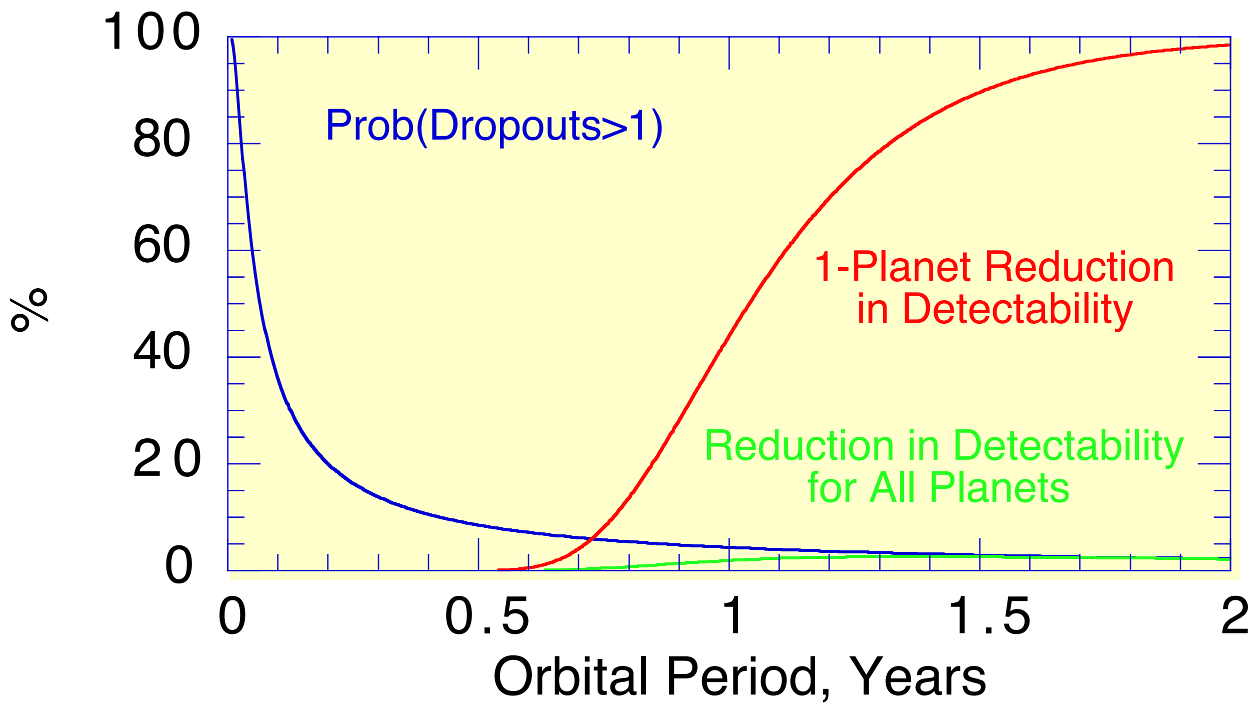
# Completed Star Plate




Transit wire on an $m_V$=9 star hole with an $m_V$=14 nearby background star in the upper left.

Completed star plate with 1600 laser drilled holes, 42 transit wires and 5 fiber optics for bright stars.

# Effect of Data Dropouts on Performance



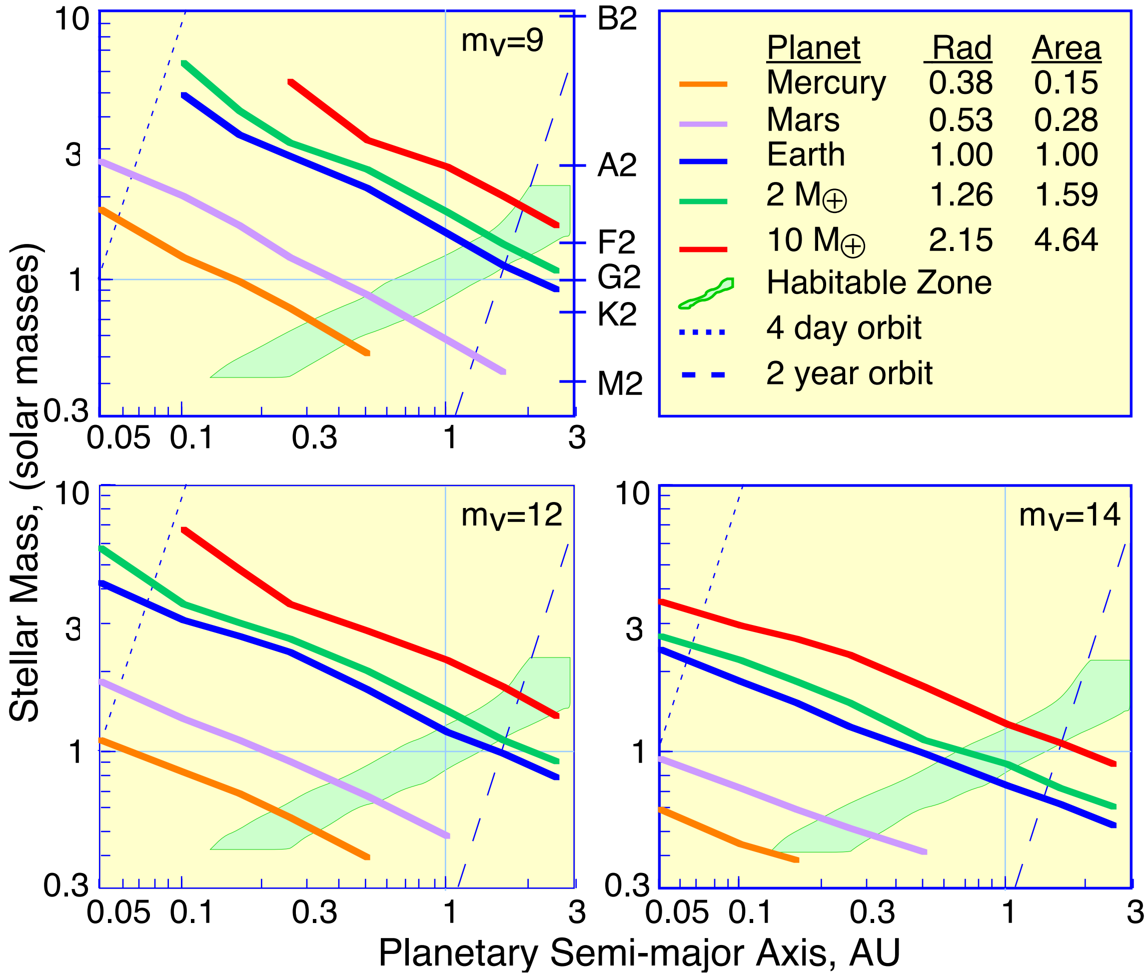

Kepler is robust against infrequent data losses. Every three months the spacecraft is rotated 90° to reposition the solar panels, resulting in a loss of 1.1% of all transits.

The probability of at least one transit being lost as a function of planetary orbital period is shown in blue.

The reduction in detectability caused by the missed transit is shown in red.

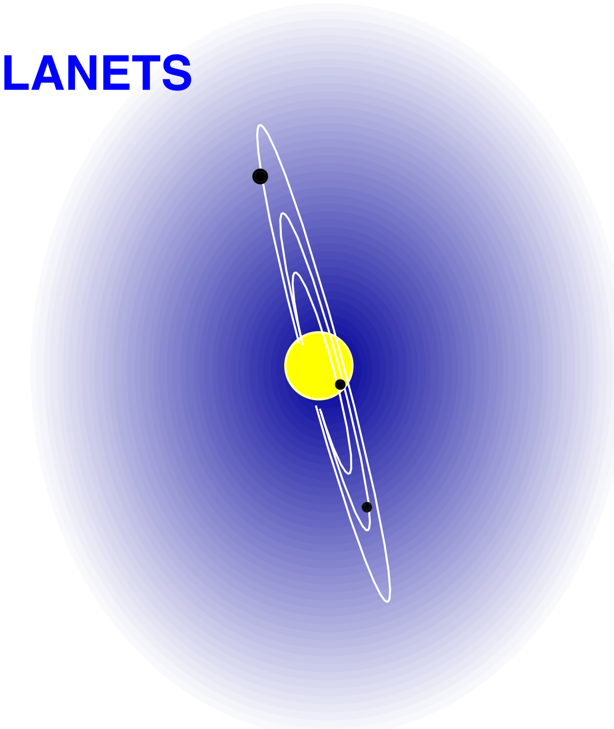
However, the expected drop in detectability is at most about 2% when averaged over all phases, as shown by the green curve.

# Detectable Planet Size




The detectable planet size is shown for a near-central transit as a function of the stellar mass and orbital size. Each plot is for a given stellar brightness. Planets of a given size are detectable to the left of each contour. Detections are based on a total SNR ≥8 and ≥3 transits in 4 years. Masses for spectral types (B2-M2) are shown.

# PHOTOMETRIC DETECTION OF EXTRASOLAR PLANETS



Transit of an Earth-size planet:

Duration 4 -16 hours;

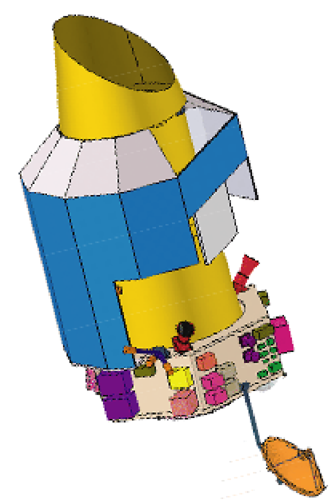
Brightness change ~1:12,000;

Orbital plane close to line-of-sight,

Prob=d*/D ≈ 1/2% for Sun-Earth case

Two transits of a star provide an orbital period.

Three or more transits with same depth, duration and temporal separation, confirm a discovery.



Planet size from:

Brightness change and star's size

Orbital size and planet's characteristic temperature from:

Orbital period and star's mass

The use of photometry to measure the brightness changes due to the transits of Earth-sized planets (1:12,000) in short period orbits (3 months to 2 years) around solar-like stars (F to early K-dwarf) is particularly effective and robust. For planets in inner orbits, the geometric probability for detecting transits is quite favorable, about 1% at 1 AU and 10% for planets like 51 Peg.

The low level variability of solar-like stars (<1:100,000) on the time scales of transits (4-16 hours) and the photometric precision that can be achieved with CCDs (<1:100,000) permit the detection of planets at least as small as the Earth.

For short period orbits, the sensitivity can be enhanced by folding of the data to average out stellar variations and thereby permit detection of planets smaller than the Earth.

# DIFFERENTIAL PHOTOMETRIC OPERATIONAL CONSIDERATIONS

- Defocus the star image to seven pixel diameter:
  - Mitigates saturation ($10^9$ phot/hr) and sensitivity to motion;
- Control pointing so star image remains on the same group of pixels:
  - Eliminates effects of inter-pixel variations in sensitivity;
- Operate CCDs near full-well capacity:
  - Dark current and read-noise effects become negligible;
- Use differential photometry:
  - Brightness of each star is re-normalized to the ensemble of stars in each quadrant of each CCD;
  - Each quadrant is readout with a single amplifier;
- Transits only last several hours:
  - Long term photometric stability not necessary;
- Place the photometer in a heliocentric orbit (SIRTF-like):
  - Provides for a very stable thermal and stray light environment.

# Expected Results

**Perform a census of planets with periods from days to a few years based on monitoring 100,000 dwarf stars for 4 years and to detect:**

**Transits of terrestrial planets:**

- About 50 planets if most have R~1.0 $R_\oplus$ (M~1.0 $M_\oplus$ )
- About 185 planets if most have R~1.3 $R_\oplus$ (M~2.2 $M_\oplus$ )
- About 640 planets if most have R ~2.2 $R_\oplus$ (M~10 $M_\oplus$ )
- About 70 cases (12%) of 2 or more planets per system

**Modulation of reflected light of giant inner planets:**

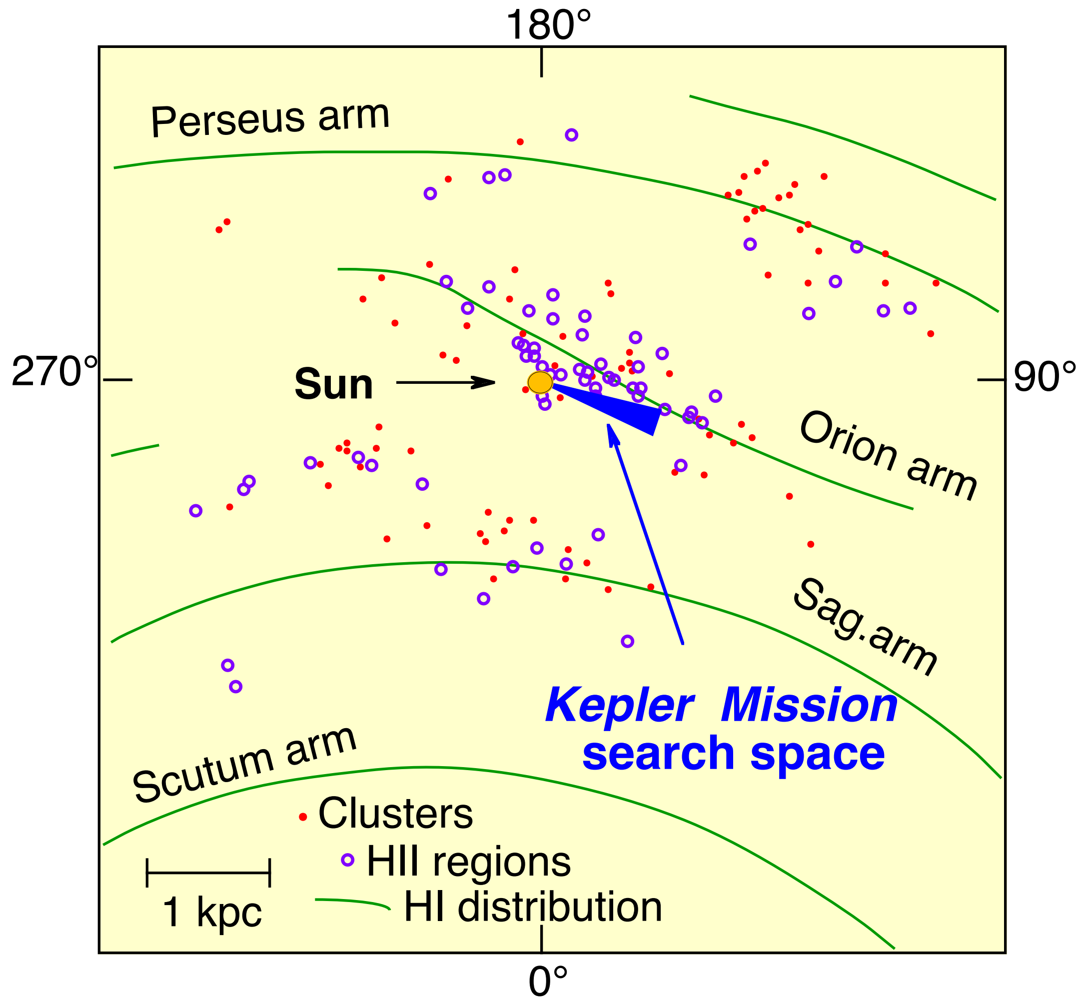
- About 870 planets with periods ≤1 week, 35 with transits
- Albedos for 100 giants planets also seen in transit

**Transits of giant planets:**

- About 135 inner-orbit planet detections
- Densities for about 35 giants planets from radial velocity data
- About 30 outer-orbit planet detections

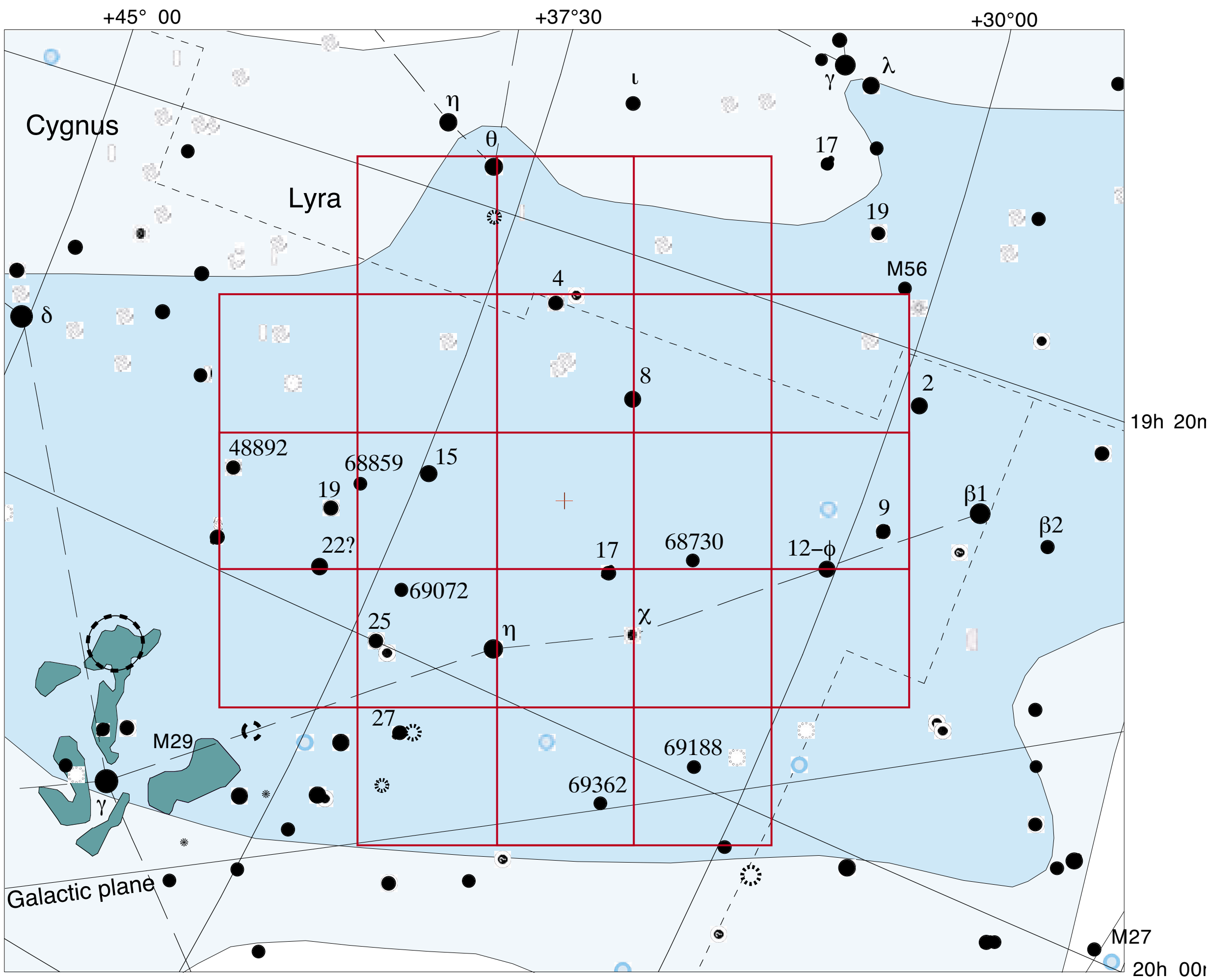
**Expect a total of ~1700 planet detections**

# Extended Solar Neighborhood



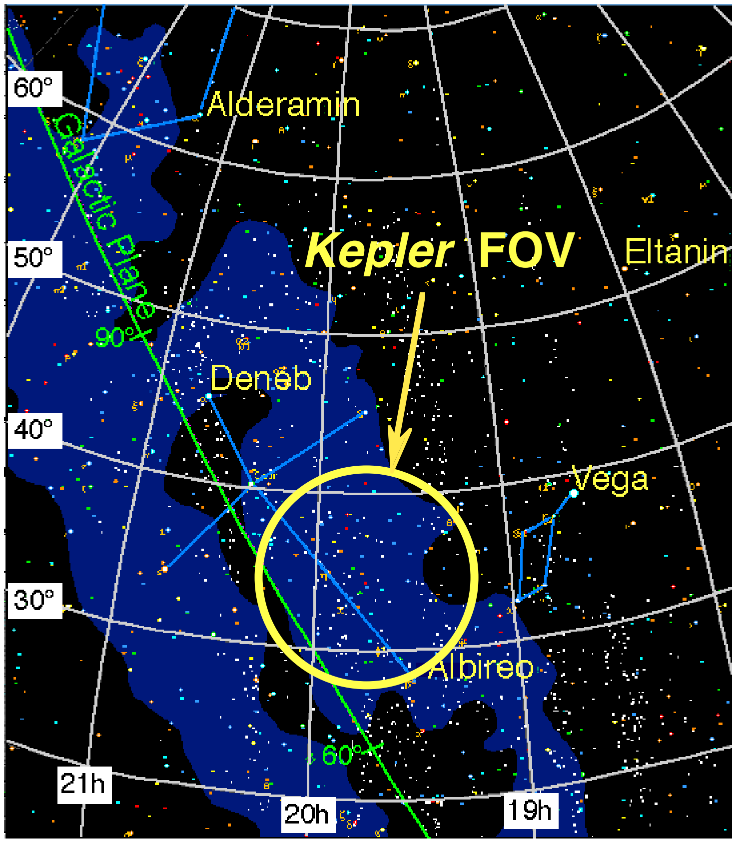

The stars sampled are similar to the immediate solar neighborhood. Young stellar clusters, ionized HII regions and the neutral hydrogen, HI, distribution define the arms of the Galaxy.

# FIELD OF VIEW IN CYGNUS



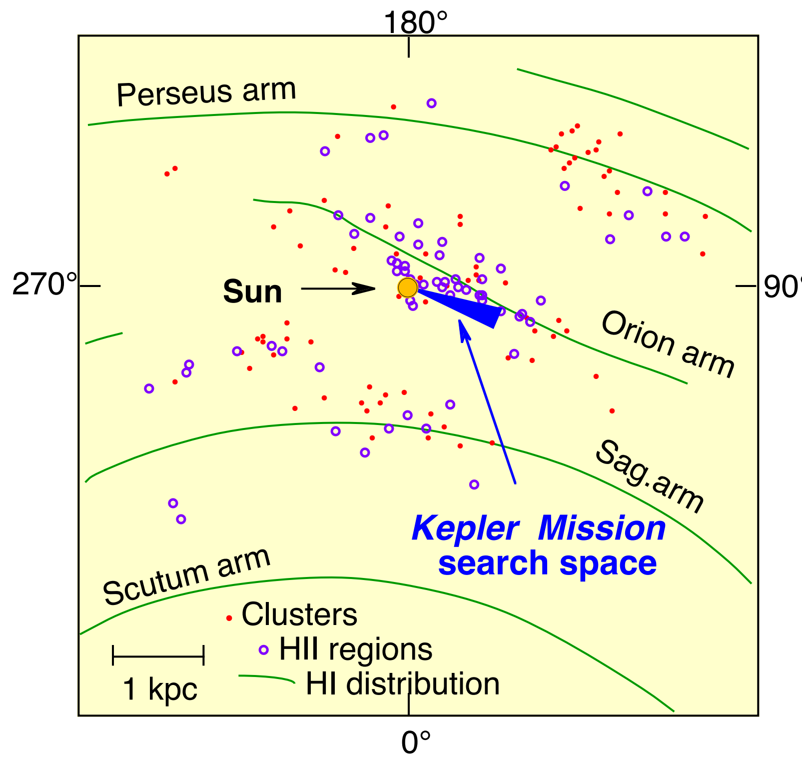

A region of the extended solar neighborhood in the Cygnus region along the Orion arm has been chosen. The star field is far enough from the ecliptic plane so as not to be obscured by the Sun. The orientation of the 21 CCD modules is shown in red. The alignment is chosen to place the brightest stars in the FOV in the gaps.

## Field of View in Cygnus




A region of the extended solar neighborhood in the Cygnus region along the Orion arm has been chosen. The star field is far enough from the ecliptic plane so as not to be obscured by the Sun. This field also virtually eliminates any confusion resulting from occultations by asteroids and Kuiper-belt objects. Comet-sized objects in the Oort cloud subtend too small an angular size and move too rapidly to be a problem. 8/98

## Extended Solar Neighborhood



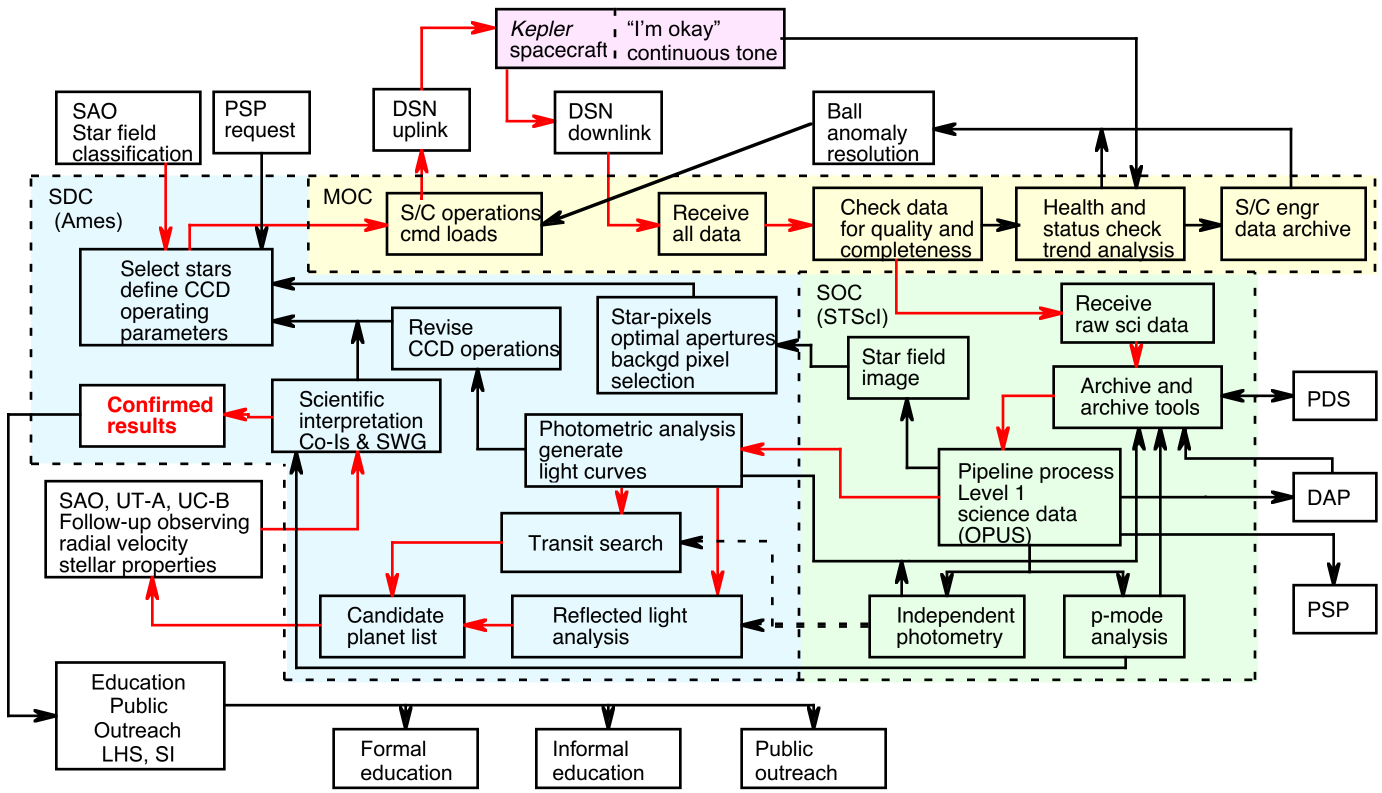

Schematic of the Galaxy. The stars sampled are similar to the immediate solar neighborhood. Young stellar clusters, ionized HII regions and the neutral hydrogen, HI, distribution define the arms of the Galaxy. The FOV location is not critical to the results of the mission, other than providing a large sample of main-sequence stars. 8/98

Focal Plane

# SCIENTIFIC GOALS AND OBJECTIVES OF THE *KEPLER MISSION*

- Determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars
- Determine the distribution of sizes and orbital semi-major axes of these planets
- Estimate the frequency and orbital distribution of planets in multiple-stellar systems
- Determine the distributions of semi-major axis, albedo, size, mass and density of short-period giant planets
- Identify additional members of each photometrically-discovered planetary system using complementary techniques
- Determine the properties of those stars that harbor planetary systems

# GROUND SEGMENT




The primary operations path used to meet the scientific Goals and Objectives is indicated in red.

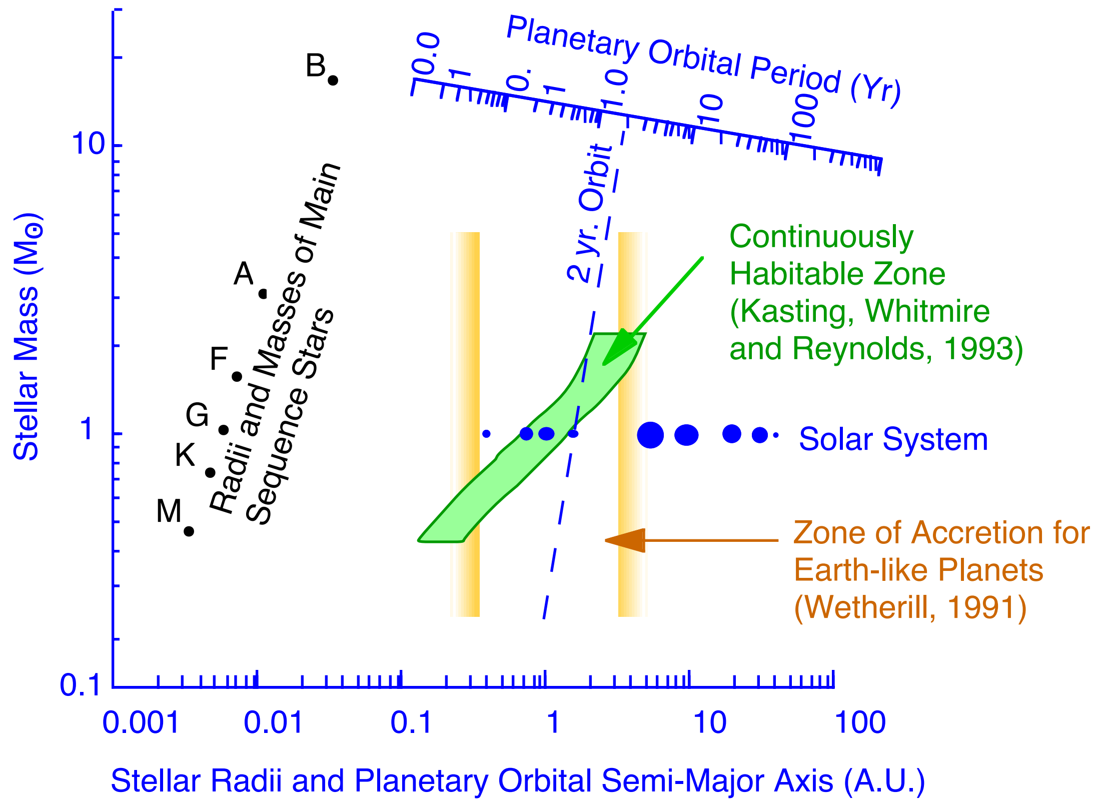
MOC: Mission Operations Center
SDC: Science Data Center
SOC: Science Operations Center

ARC: Ames Research Center
LHS: Lawrence Hall of Science
SAO: Smithsonian Astrophysical Observatory
SI: SETI Institute
STScI: Space Telescope Science Institute
UT-A: University of Texas at Austin
UC-B: University of California - Berkeley

DAP: Data Archive Program
DSN: Deep Space Network
PDS: Planetary Data System
PSP: Participating Science Program

Co-I: Co-Investigator
SWG: Science Working Group

# THE TERRESTRIAL ACCRETION ZONE AND THE HABITABLE ZONE FOR VARIOUS STELLAR TYPES



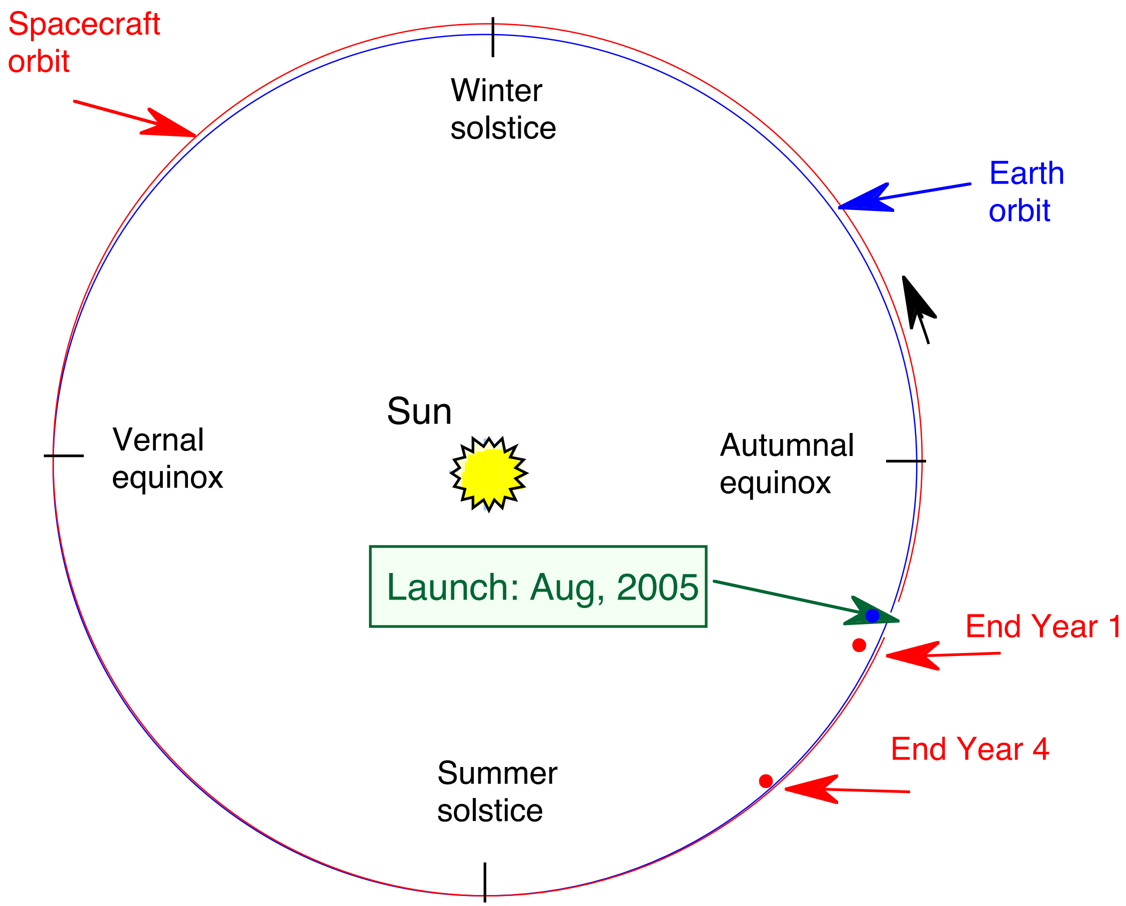

Each main sequence spectral type (B, A, F, G, K, M) is shown in black to indicate the star's mass and radius on the left side of the diagram. The Habitable Zone (green) and the planets in our solar system (blue) are shown. The *Kepler Mission* is capable of detecting terrestrial and larger planets in orbits of up to two years.

The continuously habitable zone is bounded by the range of distances from a star for which liquid water would exist and by the range of stellar spectral types for which planets had enough time to form and complex life had enough time to evolve (no earlier than F) and for which stellar flares and atmospheric condensation due to tidal locking do not occur (no later than K). The figure shows the habitable zone as calculated by Kasting, Whitmire, and Reynolds, (1993) for main sequence stars as a function of spectral type.

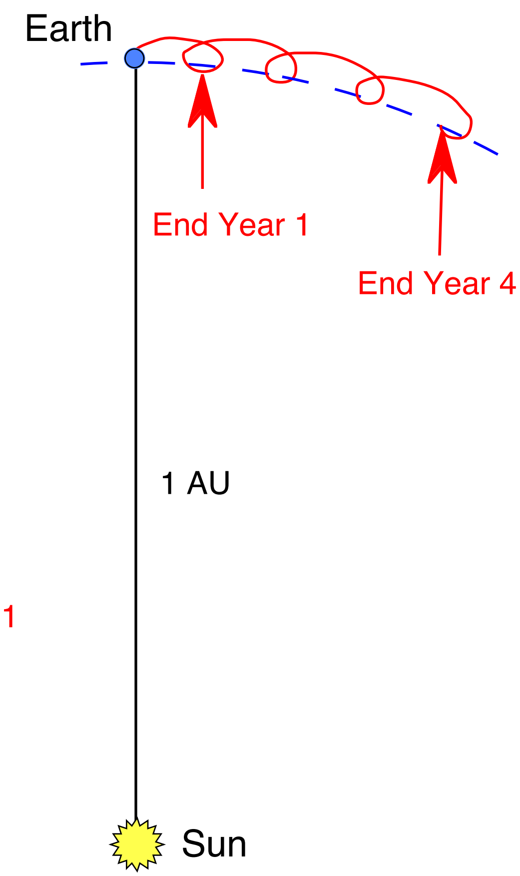
Numerical modeling by Wetherill (1991) shows that the accumulation of planetesimals during molecular cloud collapse can be expected to produce, on the average, four inner planets between the orbits of Mercury and Mars. Two of these are approximately earth-sized and two are smaller. Thus, a search for terrestrial planets should include this region.

The *Kepler Mission* will perform an unbiased search for all orbital periods $\leq$2 year's, that is, out to a martian orbit, and for all spectral types. It will not be affected by solar or extra-solar zodiacal background and can detect planets within binary star systems.

# Earth-Trailing Heliocentric Orbit




Heliocentric Coordinates




Sun-Earth Fixed Coordinates

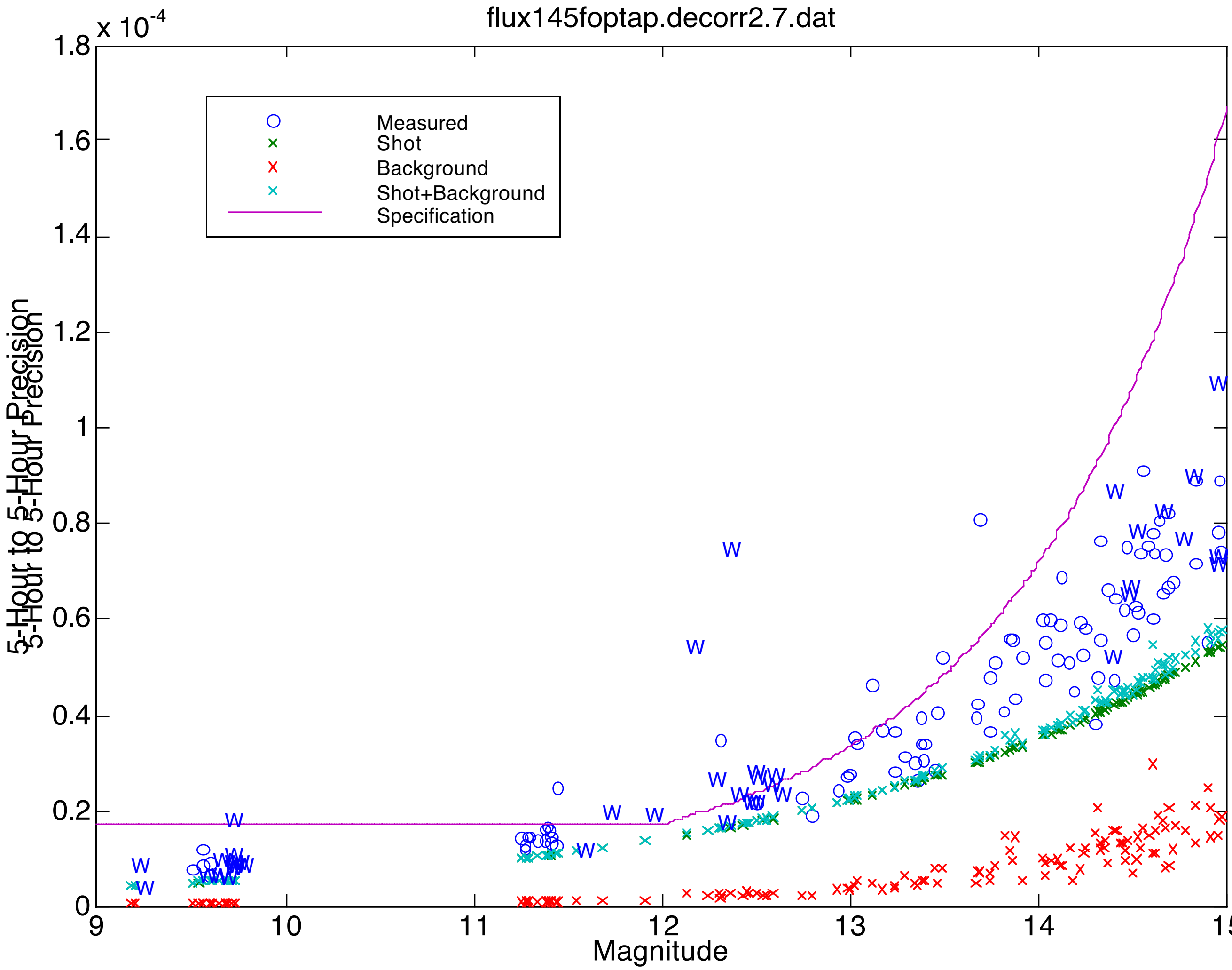
| | Earth | Spacecraft |
|---|---|---|
| Period (days) | 365.25 | 372.50 |
| Semi-major (AU) | 1.00000 | 1.01319 |
| eccentricity | 0.01675 | 0.03188 |

The selected region of the sky must be continuously viewed to achieve the mission objects. Hence, the spacecraft must point out of the ecliptic to avoid the Sun on an annual basis and it must orbit far from the Earth to avoid repeated earth blockage every 90 minutes or so. An Earth-trailing heliocentric orbit has been selected.

The heliocentric orbit is similar to that of the Earth about the Sun. However, the orbital period is one week longer (372.5 days), so that the spacecraft slowly drifts away from the Earth as both the Earth and the spacecraft orbit the Sun. After eight years the spacecraft will be 0.9 AU ($1.35 \times 10^8$ km) away from the Earth.

When viewed from the Earth, the spacecraft always appears in the sky in the ecliptic plane and just rises above the horizon at local noon; is overhead at sunset; and sets at local midnight (except for the first year when it starts in the anti-solar position and drifts to this position 90° from the Sun).

# LONG DURATION TEST ALL CONFOUNDING FACTORS




Long Duration (10 days) with all confounding factors: Except for several wired stars, the average trend of the precision values is below the precision upper limit.

# MISSION CONCEPT

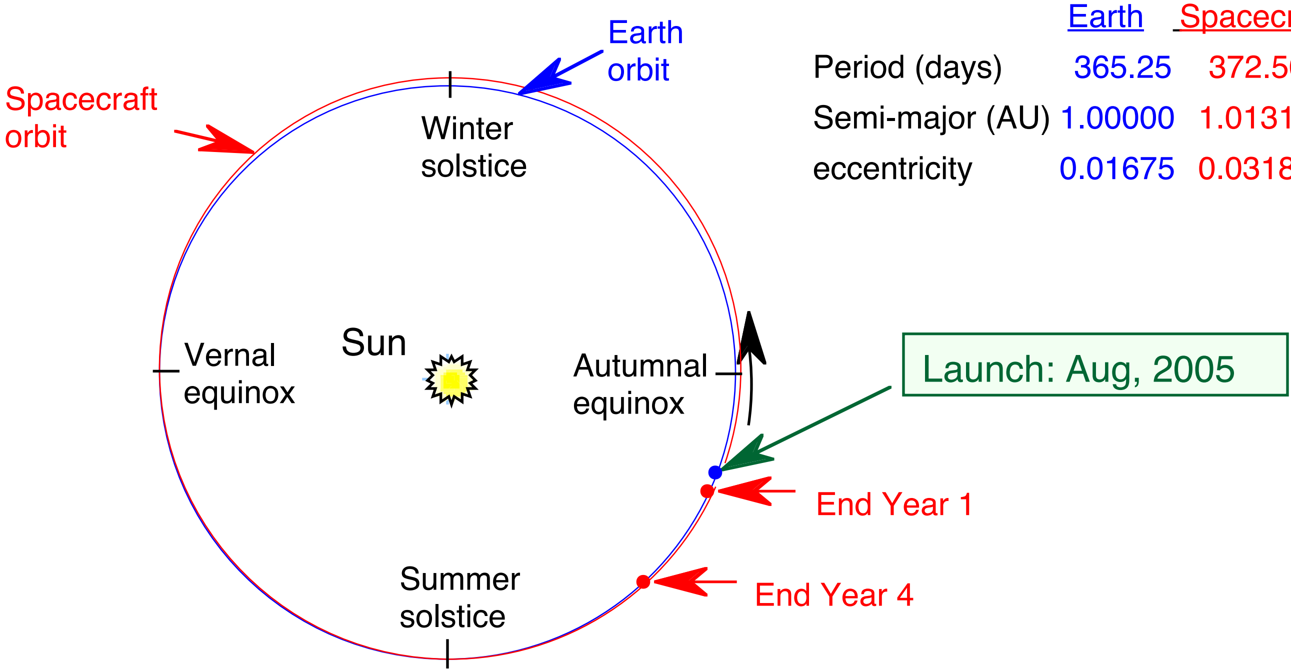
Telescope design: 105 deg$^2$ FOV

Instrument sensitivity: 4σ detection in 6.5 hours for Earth-size transit
on $m_V$ = 12 solar-like star

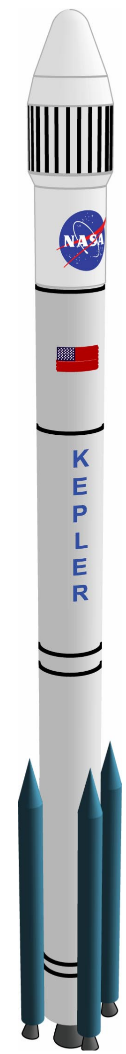
Information handling: 100,000 main-sequence stars

Launch on a Delta II to a heliocentric orbit

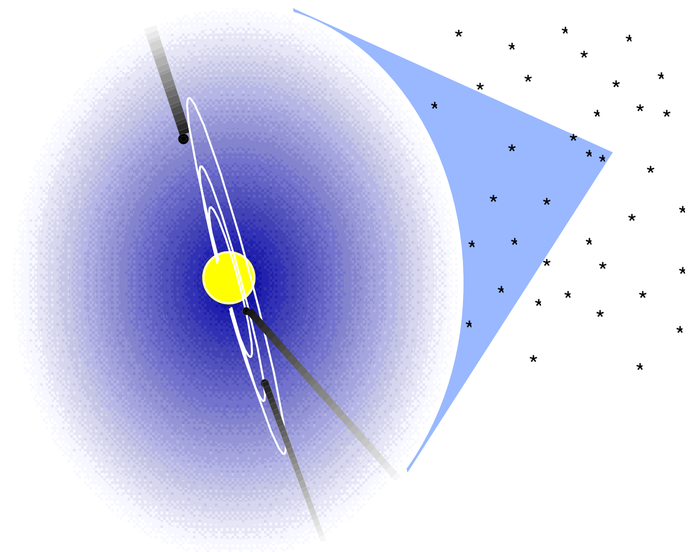
Stare at a single fixed star field for 4 year mission duration




| | Earth | Spacecraft |
|---|---|---|
| Period (days) | 365.25 | 372.50 |
| Semi-major (AU) | 1.00000 | 1.01319 |
| eccentricity | 0.01675 | 0.03188 |



# Mission Concept



Use a one-meter Schmidt telescope:

105 deg$^2$ FOV and an array of 42 CCD

Continuously and simultaneously

monitor 100,000 main-sequence stars

Instrument sensitivity:

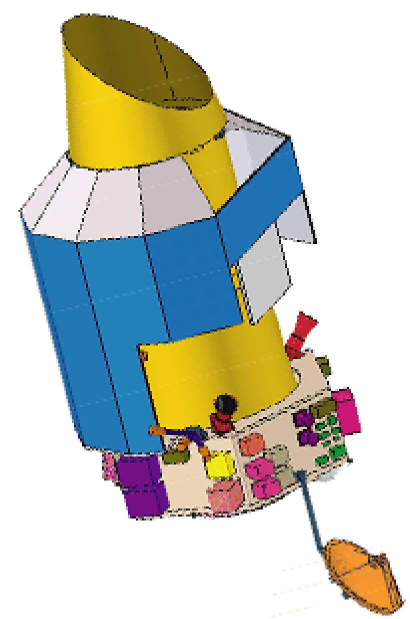
$4\sigma$ detection in 6.5 hours for Earth-size transit

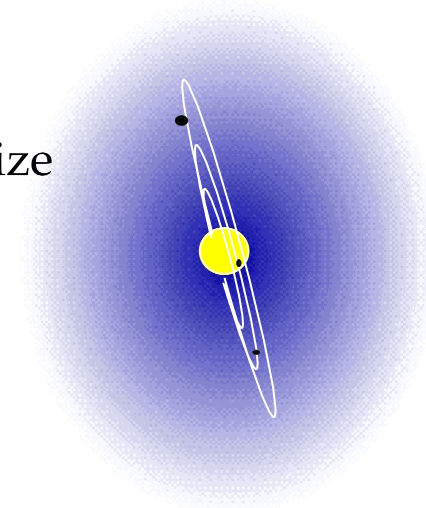
on $m_V = 12$ solar-like star

Launch on a Delta II :

Heliocentric orbit

4 year mission duration



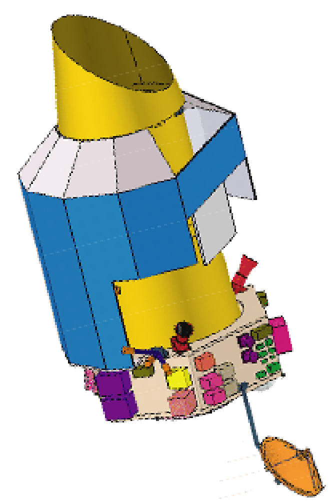


## Scientific Goals and Objectives

- Survey the extended solar neighborhood to detect and characterize terrestrial and larger planets in or near the habitable zone
- Explore the structure and diversity of planetary systems with an unbiased survey

## Mission Concept

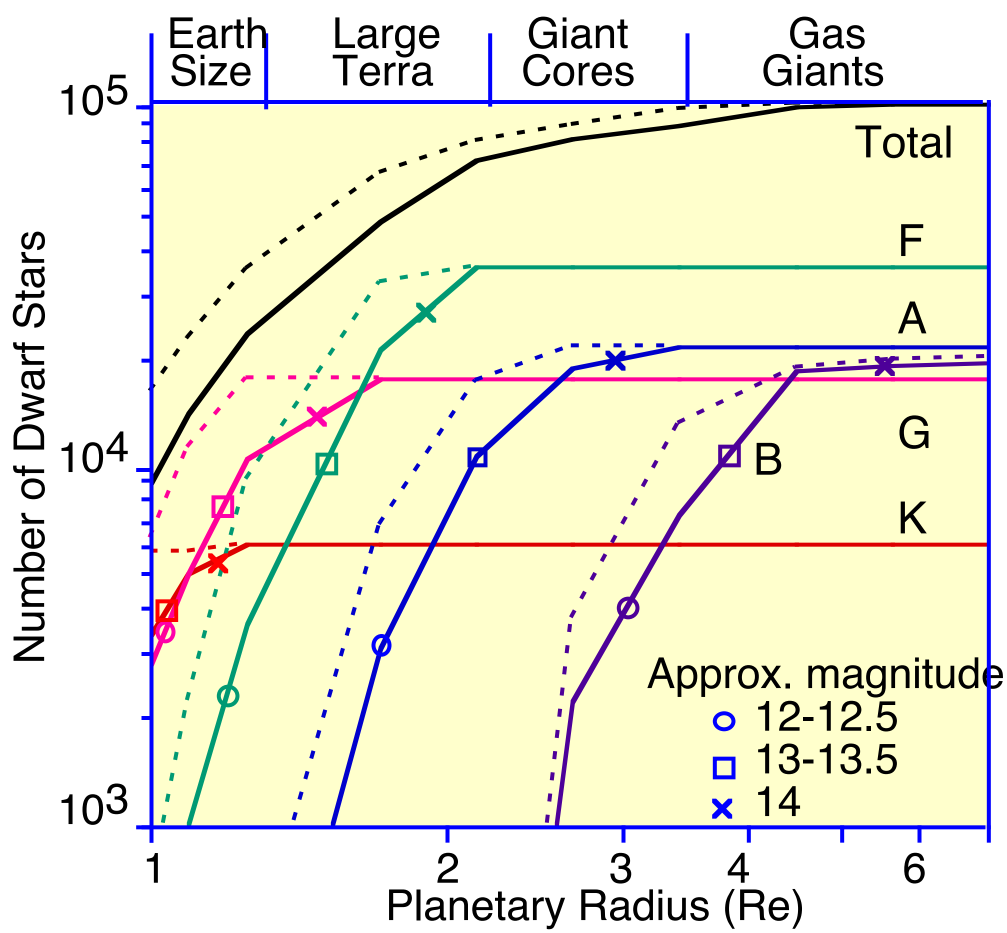
- Use transit photometry to continuously and simultaneously monitor 100,000 main-sequence stars for 4 years
- Three transits of the same depth, duration and consistent temporal separation are used to confirm each discovery
- The planet size, orbit and characteristic temperature are calculated from the data



## Expected Results

- About 50 planets if most have **$R \simeq 1.0\ R_\oplus$ ($M \simeq 1.0\ M_\oplus$)**
- About 185 planets if most have **$R \simeq 1.3\ R_\oplus$ ($M \simeq 2.2\ M_\oplus$)**
- About 640 planets if most have **$R \simeq 2.2\ R_\oplus$ ($M \simeq 10\ M_\oplus$)**
- About 870 giant planets with periods $\leq$1 week from modulation of reflected light (35 with transits) **($R>10\ R_\oplus$ , $M>100\ M_\oplus$)**
- About 135 inner-orbit and 30 outer–orbit giant planets **($R>2.2\ R_\oplus$ , $M>10\ M_\oplus$)**

# NUMBER OF DWARF STARS FOR WHICH PLANETS CAN BE DETECTED




The solid lines show the number of dwarf stars of each spectral type for which a planet of a given radius can be detected at ≥8_. The conservative numbers are based on 4 near-grazing transits with a 1 yr period and stars with mv≤14. The dashed lines show a significant increase in the number of stars when assuming 4 near-central transits with a 1-yr period. An even greater increase is realized for 8 near-grazing transits with a 0.5-yr period.

The probability for a planet to transit a star is d*/D, the diameter of the star to the diameter of the orbit. Thus, the chances of detecting a planet in the habitable zone are about 1/2%. Therefore, many tens of thousands of stars need to be monitored continuously in order to detect hundreds of planets.

The requirement that the single FOV of the sky being monitored never be blocked by the Sun and that the FOV have a high density of stars has lead to a selection of a region along the Cygnus arm of the Galaxy. The recent digitization of the POSS by USNO (D. Monet) was used to determine the number of main-sequence stars in the 105 sq. deg. FOV for $m \leq 14$ to be 220,000 of all spectral types and luminosity classes. From the HR-diagram and the luminosity function (Wielen, 1983), the number of usable dwarf stars is estimated to be 100,000.

The brightness and size of a star along with the transit duration and orbital period determine the minimum planet size that can be detected.

# Observing Plan

Continuously and simultaneously monitor
100,000 main-sequence stars:

Observe a single field in Cygnus
with a 105 $deg^2$ FOV Schmidt telescope

Mission life-time of 4 years.

# Expected Results

From transits of Earth-class inner-orbit planets:

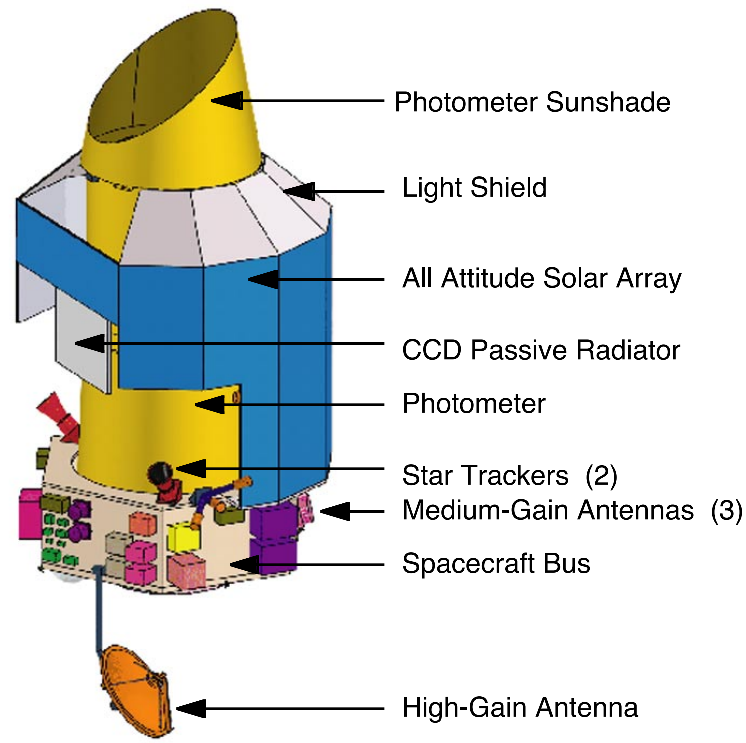
- About 50 planets if most have $R \sim 1.0\ R_\oplus$
- About 185 planets if most have $R \sim 1.3\ R_\oplus$
- About 640 planets if most have $R \sim 2.2\ R_\oplus$
- About 70 cases (12%) of 2 or more planets per system

From transits of giant planets:

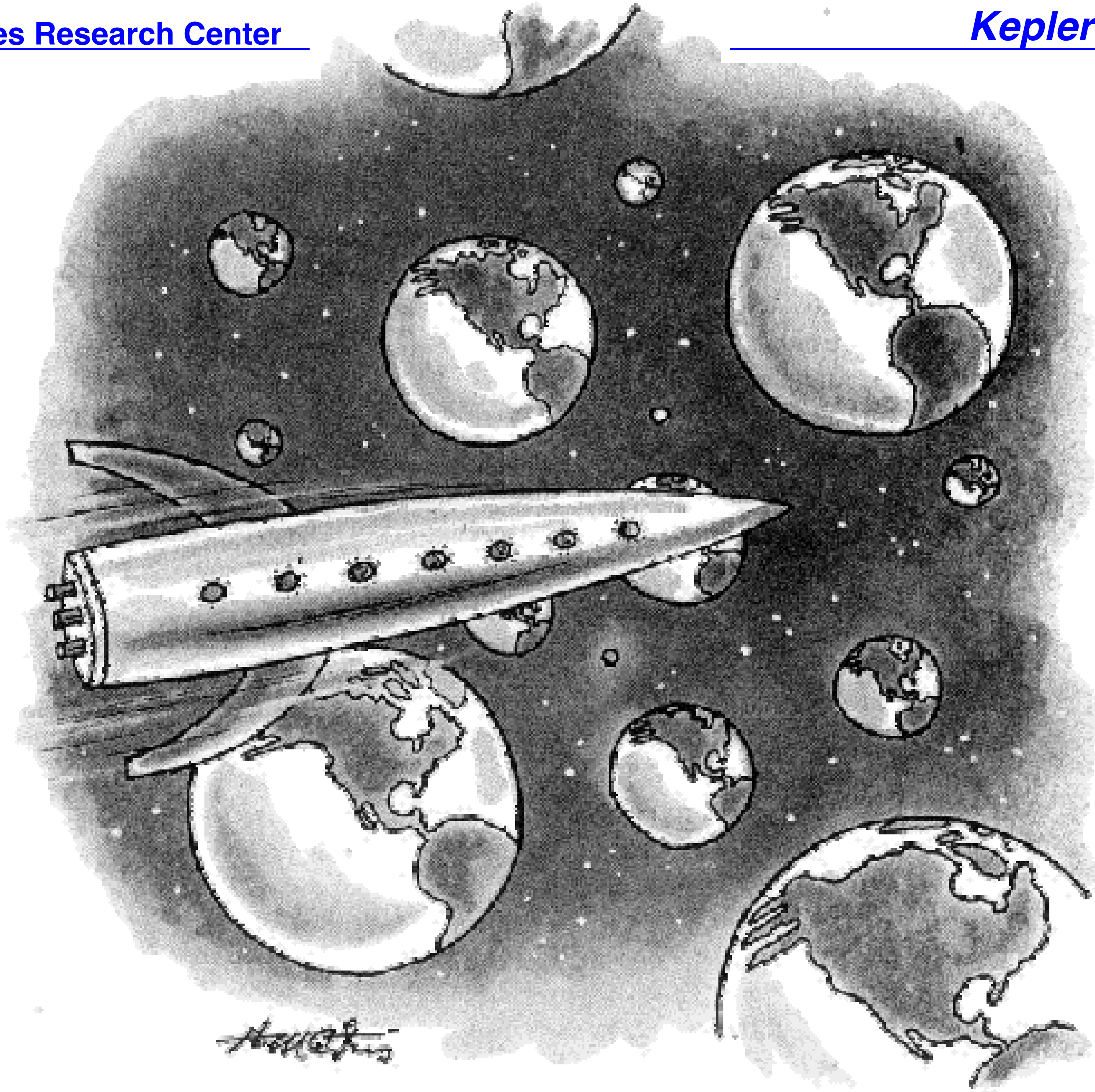
- About 135 inner-orbit planet detections
  Densities for 35 using radial velocity data (F5-K5)
- About 30 outer-orbit planet detections

From modulation of reflected light of major inner planets:

- About 870 with periods $\leq$ 1 week
- Albedos for the 100 giant planets also seen in transit

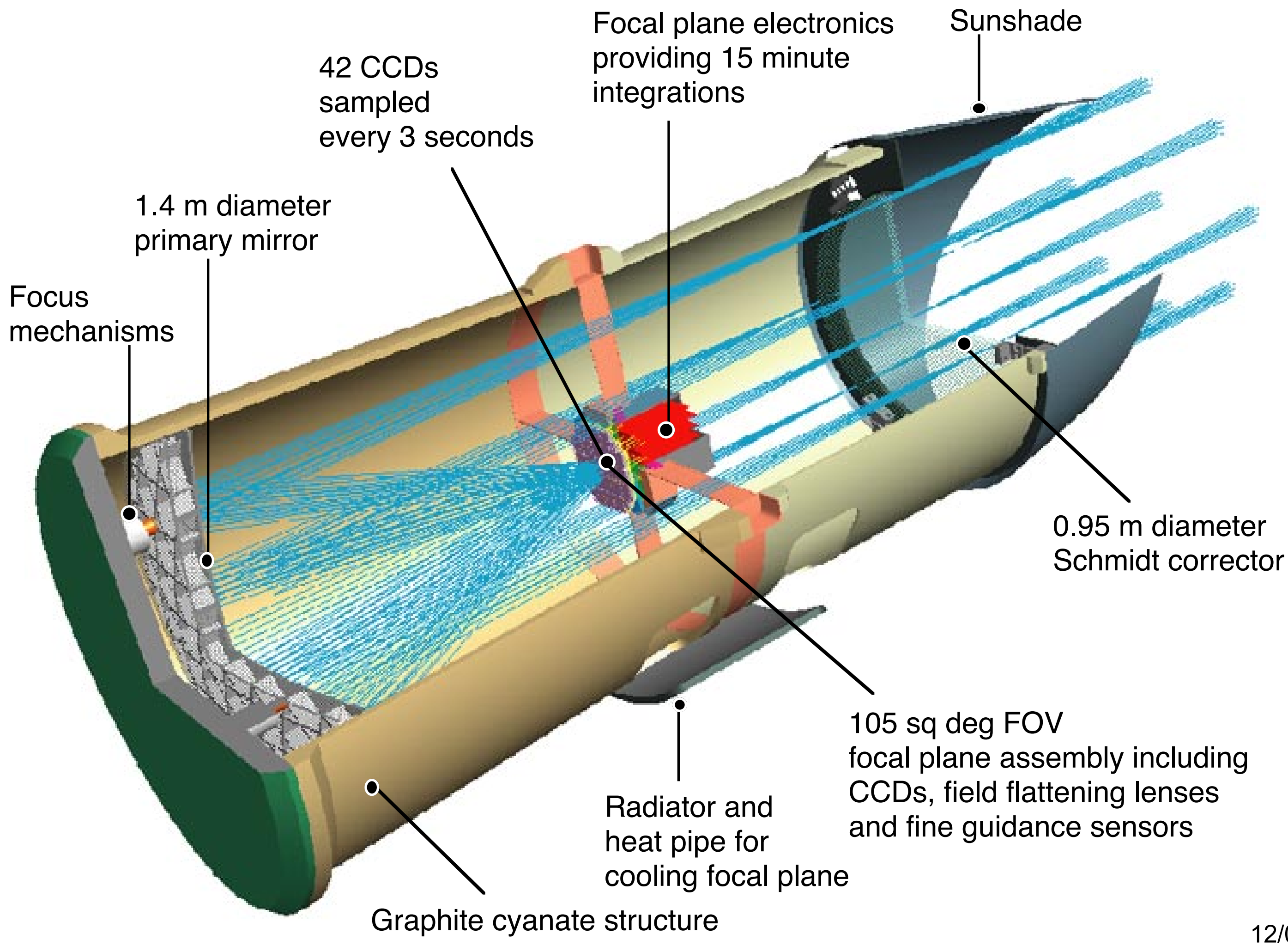



**Expect a total of ~1700 planet detections**

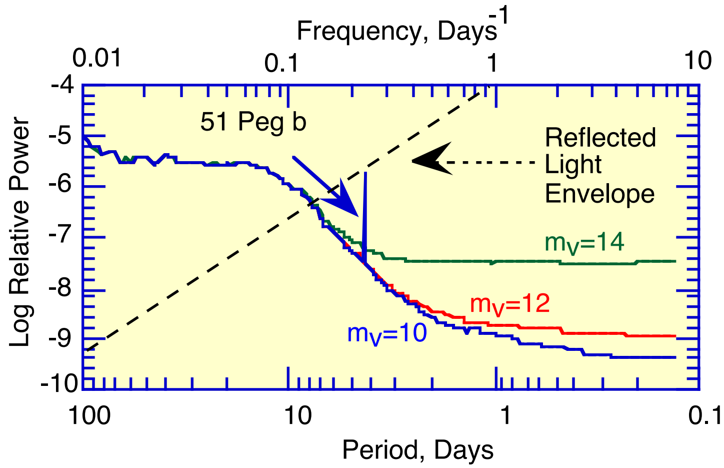


*“Well, this mission answers at least <u>one</u> big question: Are there other planets like ours in the universe?”*

# KEPLER PHOTOMETER



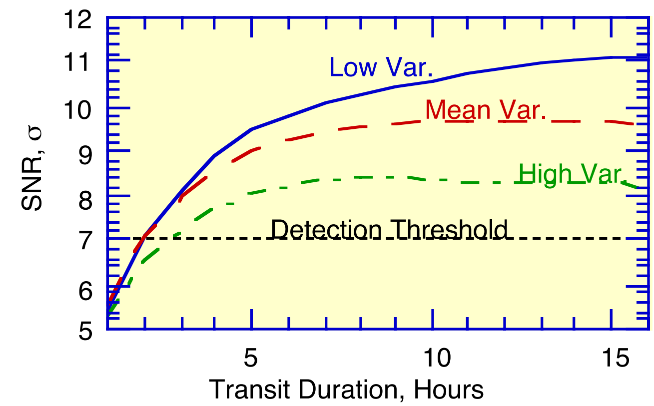
## Power Spectral Densities




The blue, red and green curves are the total noise for different stellar brightnesses. The total noise includes stellar variability, shot noise, CCD noise and pointing noise.

The blue spike at 4.2 days is the reflected light signature of a 51-Peg-type planet with an albedo of 0.5 (matching that of Jupiter) in orbit about an $m_V$=10 star. At other periods, the strength of this spike would vary, as given by the black dotted reflected light envelope. 12/00

## SNR Dependence on Transit Duration and Stellar Variability




The three curves give the signal to noise ratio (SNR) for four combined Earth-size ($R_\oplus$=1.0) transits about an $m_V$=12 solar-like star at times of low, medium, and high stellar variability.

Even for the high variability case, the probability is still greater than the threshold for detecting a sequence of grazing 6.5 hrs transits of an Earth-size planet. Stars with a lower variability permit detection of planets smaller than the Earth.

12/00

# Science Team

William Borucki, Principal Investigator, NASA Ames Research Center

David Koch, Deputy Principal Investigator, NASA Ames Research Center

## Co-Investigator's Working Group

| | |
|---|---|
| G. Basri | UC-Berkeley |
| W. Cochran | McDonald Obs./U. Texas |
| E. DeVore | SETI Institute |
| E. Dunham | Lowell Observatory |
| J. Geary | SAO |
| R. Gilliland | STScI |
| A. Gould | Lawrence Hall of Sci/UC-B |
| J. Jenkins | SETI Institute |
| Y. Kondo | NASA/GSFC |
| D. Latham | SAO |
| J. Lissauer | NASA/ARC |

## Science Working Group

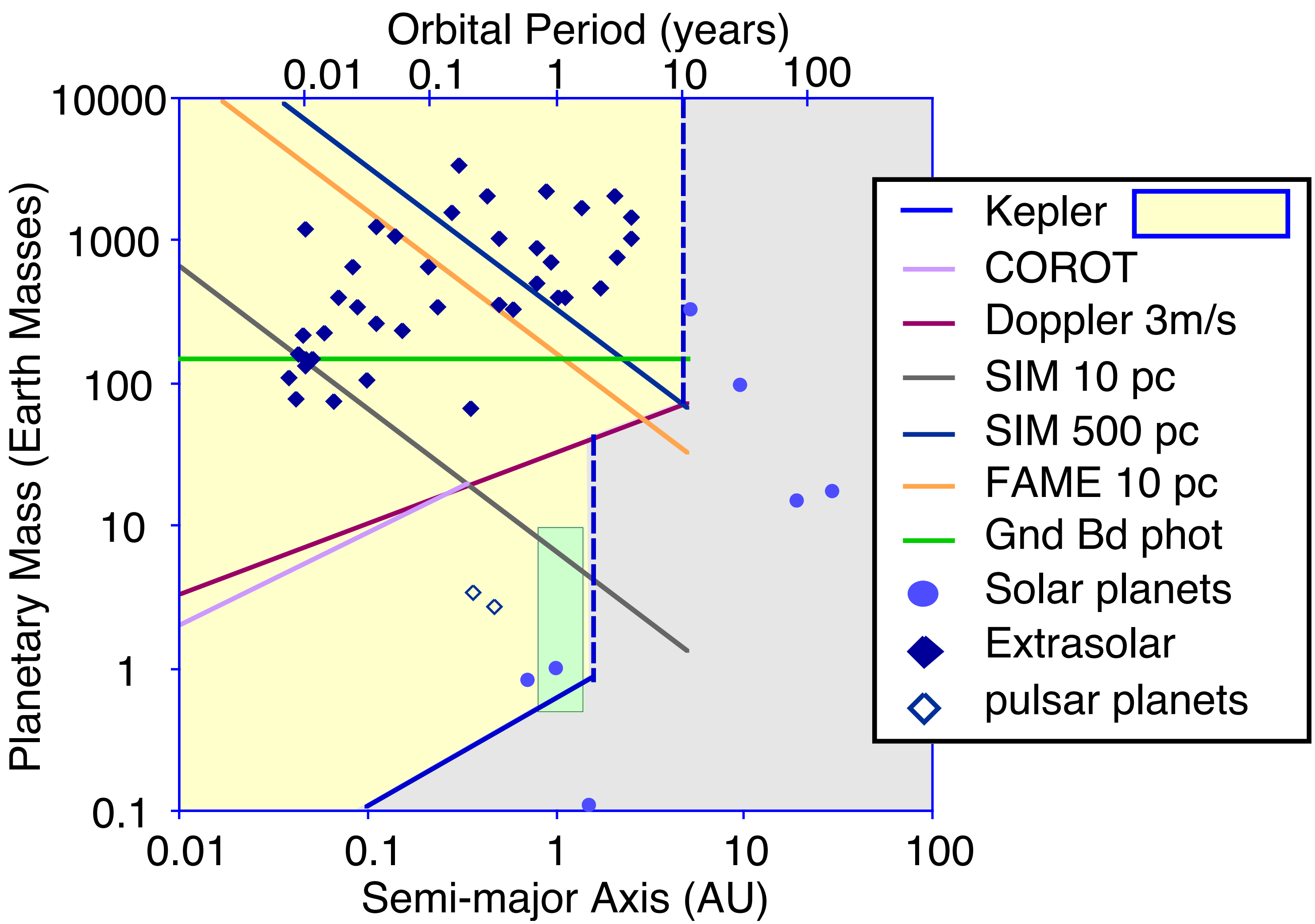
| | |
|---|---|
| A. Boss | Carnegie Institute of Washington |
| T. Brown | HAO/NCAR |
| D. Brownlee | University of Washington |
| J. Caldwell | York University |
| A. Dupree | SAO |
| S. Howell | Planetary Science Institute |
| G. Marcy | UC-Berkeley |
| D. Morrison | NASA/ARC |
| T. Owen | University of Hawaii |
| H. Reitsema | Ball Aerospace |
| D. Sasselov | SAO |
| J. Tarter | SETI Institute |

# Management Team

Larry Webster, Project Manager, NASA Ames Research Center

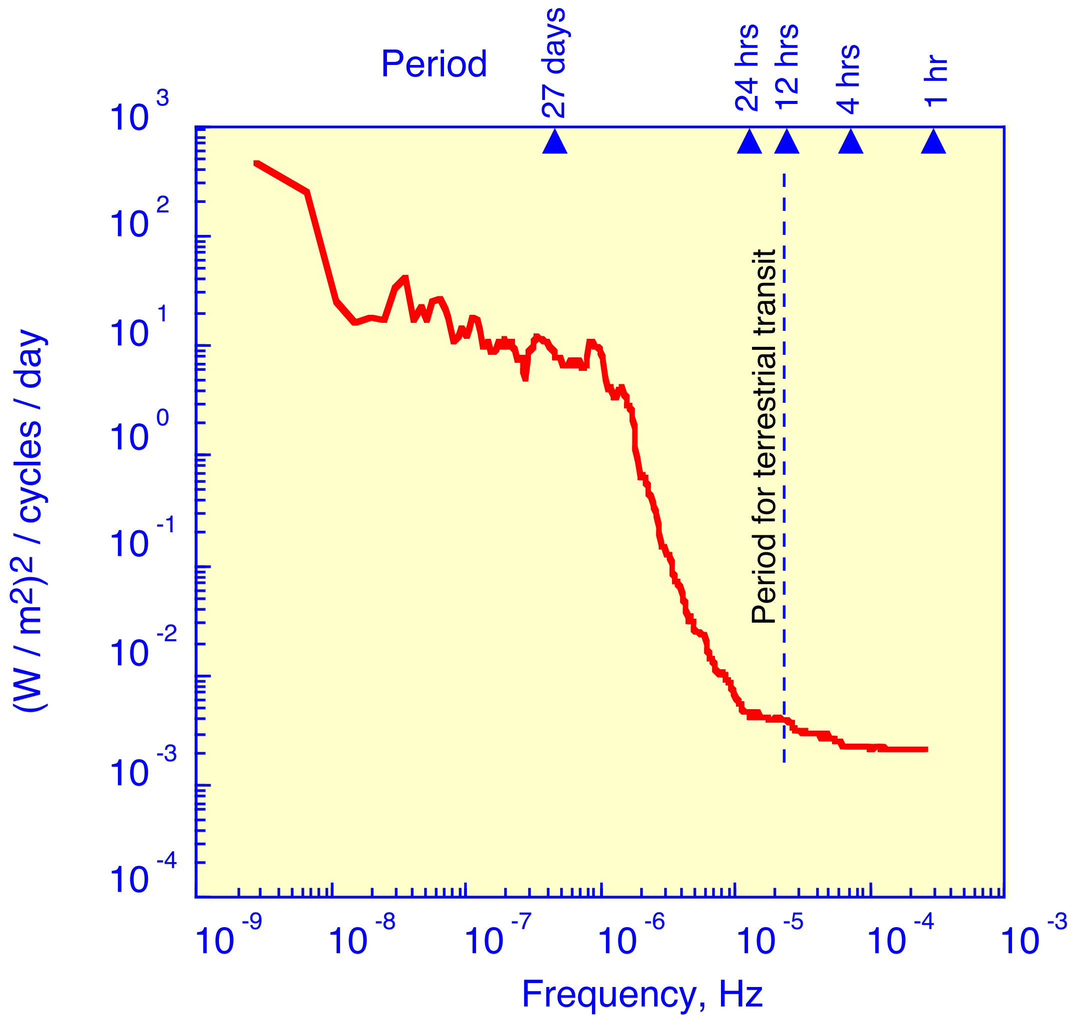
Industrial Partner, Ball Aerospace, Boulder, CO

# KEPLER SEARCH SPACE SENSITIVITY




The limiting sensitivities for planet detection around a solar-like star are shown for photometry with *Kepler* (yellow region) and COROT; Doppler spectroscopy at 3 m/s; and astrometry with SIM at 2$\mu$as and FAME at 50$\mu$as. The range of habitable planets in the HZ is shown in green. The ~50 known extrasolar planets are also shown.

# POWER SPECTRUM OF SUN FROM SMM DATA FOR 1985-1989

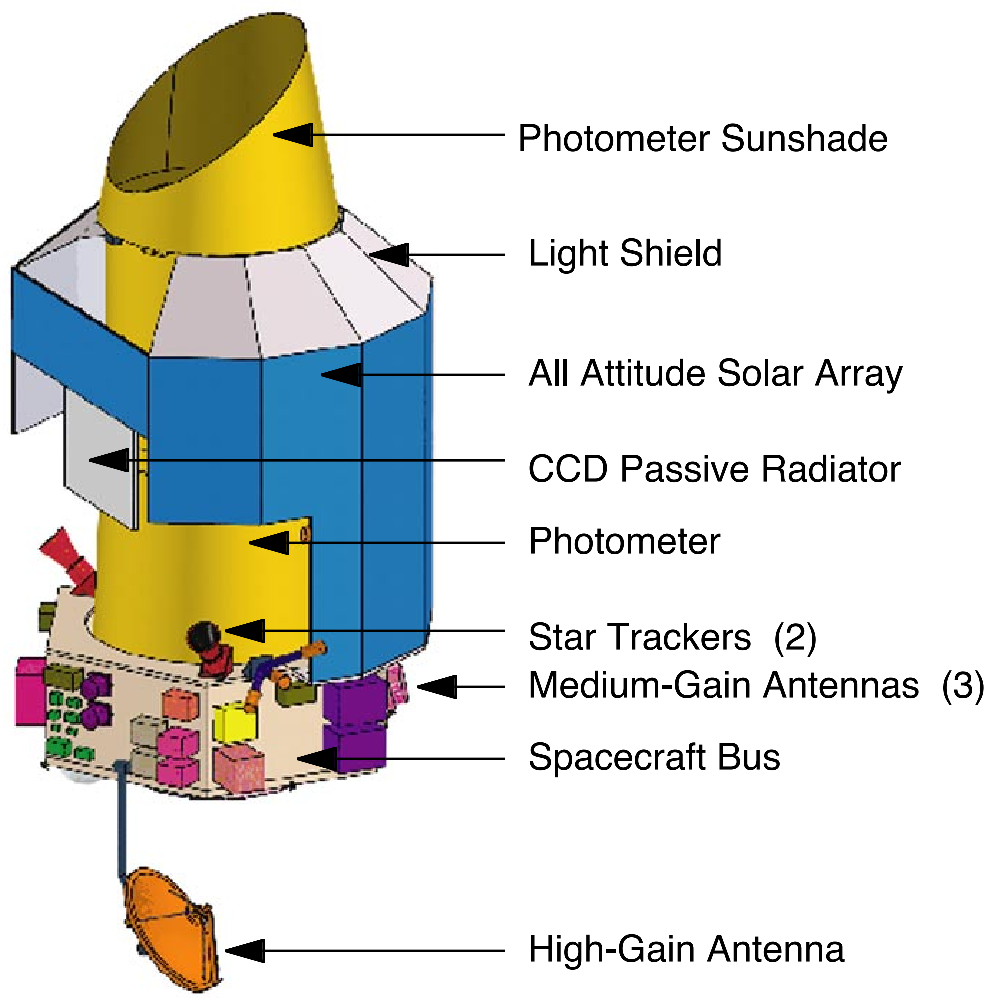


Solar-like stars (F- G- and K-dwarfs) are among the quietest stars known. Radiometry data from the Solar Maximum Mission, Upper Atmosphere Research Satellite (UARS) and most recently from the SOlar and Heliospheric Observatory (SOHO) show the solar variability to be less than one part in 100,000 for periods of four to twelve hours. (These data are believed to show 30% more variability than what would be expected had the UV been excluded.)

If solar-like stars have variability similar to that of the Sun, then the intrinsic brightness fluctuations are expected to range from $10^{-3}$ at the rotation period of the star (~weeks) due to the presence of large star spot groups to values of less than $10^{-5}$ with a duration of hours due to turbulent motions and gravity waves in the stellar photosphere (Fröhlich, 1987).

Brightness changes with durations greater than 16 hours will have little affect on the detectability of transits, which range in duration from 4 hours for a Mercury grazing transit to 16 hours for a Mars central transit.

# KEPLER SPACECRAFT




12/00

# Strengths of the Transit Method

- Detect terrestrial planets in or near the habitable zone of stars;
- Detect planets around a wide variety of stars: A- through M-type;
- Detect planets even as small as Mars if they are in short period orbits;
- Determine the orbit, **planet size** and characteristic temperature ;
- Provide statistics on the abundance of planets in the galaxy;
- Detect planets in both singular and multiple stellar systems;
- Not hampered by the local or any unknown extrasolar-zodiacal emission;
- Not dependent on distance to object other than stellar brightness;
- All technology for implementation is in hand.

# Summary

Differential photometry of periodic planetary transits of stars is robust method for detection of extrasolar planets

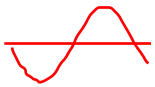
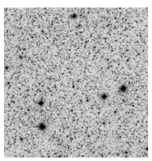
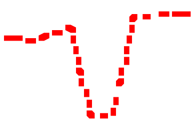
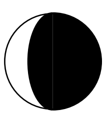
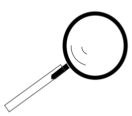
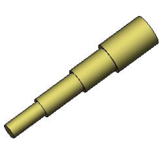
A large sample of solar-like stars is used to provide statistically meaningful results for a potentially wide variety of planets in the extended solar neighborhood orbiting a wide variety of stellar types.

The *Kepler Mission* can discover:

Planet sizes from that of Mars to greater than Jupiter;
Orbital periods from days up to two years;
An estimated 800 planetary systems seen in transit;
An estimated 900 planetary systems seen by reflected light;

Stellar rotation rates and activity cycles can also be obtained from these measurements. Analysis of p-mode data can be used to derive the stellar mass and age for those stars measured at a 1 minute cadence.

# TECHNIQUES FOR FINDING EXTRASOLAR PLANETS

| | Method | Yield | Mass Limit | Status |
|---|---|---|---|---|
|  | Pulsar Timing | $m/M$ ; $\tau$ | Lunar | Successful |
|  | Radial Velocity | $m \sin i$ ; $\tau$ | Uranus | Successful |
| | Astrometry | $m$ ; $\tau$ | | |
|  | Ground: Telescope | | Jupiter | Ongoing |
| | Ground: Interferometer | | sub-Jupiter | In development |
| | Space: Interferometer | | Uranus | Being studied |
|  | Transit Photometry | $A$ ; $\tau$ | | |
| | Ground | | Saturn | Ongoing |
| | Space | | Venus | Proposed (Kepler) |
|  | Reflection Photometry: Space | albedo $A$ ; $\tau$ | Saturn | Proposed (Kepler) |
|  | Microlensing: | $f(m,M,r,D_S,D_L)$ | sub-Uranus | Pilot projects |
|  | Direct Imaging | albedo $A$ ; $\tau$ | | |
| | Ground | | Saturn | In development |
| | Space | | Earth | Being studied |

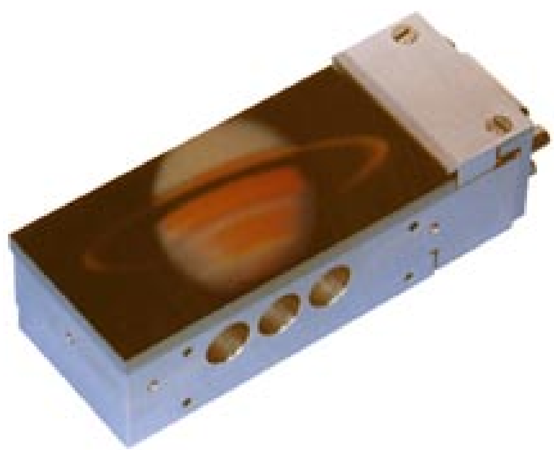
# Test Objectives and Facility Requirements

There are many confounding factors that influence the system noise and hence the detectability of transits. The purpose of the tests were to measure the effects of these factors, identify the optimal operating conditions under the influence of each factor and show that when all of the effects are taken together Earth-size transits can be reliably observed. The Test Facility incorporates the ability to measure the following effects:

| | |
|---|---|
| 1. Spacecraft jitter: | Motion to 500 millipixels each axis (expect ±3 millipixels) |
| 2. Dynamic range: | Target stars $m_v$=9 to 14. Background stars to $m_v$=19 |
| 3. Double stars: | Five magnitudes fainter at 0.5 to 5 FWHM separation |
| 4. Smearing: | Shutterless readout with other stars in the same column |
| 5. Field rotation: | Star field moved to different portions of CCD |
| 6. Temperature: | CCD operating range from -60°C to –40°C |
| 7. Focus change: | Effects of focus variations on noise, psf and plate scale |
| 8. Optimal aperture: | Operate from 3 to 11 pixel (binned) photometric aperture |
| 9. Thermal effects: | Various effects, such as, differential expansion |
| 10. Bright stars: | Effects of blooming caused by $m_v$=4 star |
| 11. Cosmic rays: | Effects of cosmic-ray hits on the CCD |

# CCD Tested

For these tests an EEV 42-80 back-illuminated CCD was selected. The CCD has 2048x4096 pixels of 13.5 $\mu$m. The overall size is 27x54mm. The pixels are binned on the CCD to 27$\mu$m. In effect it is used as a 1024x2048 device. The binning improves both the readout speed and the photometric precision. The device is read out at 1 megapixel/sec.



# Technology Demonstration Overview

The *Kepler Mission* depends on the ability to reliably measure the very small relative change in brightness of a star caused by the transit of an Earth-size planet. We have constructed a high-fidelity Testbed Facility of the end-to-end photometry system. This has been used to show that under all of the expected operating conditions which can add noise to the measurement, the signature of an Earth-size transit is readily detectable.

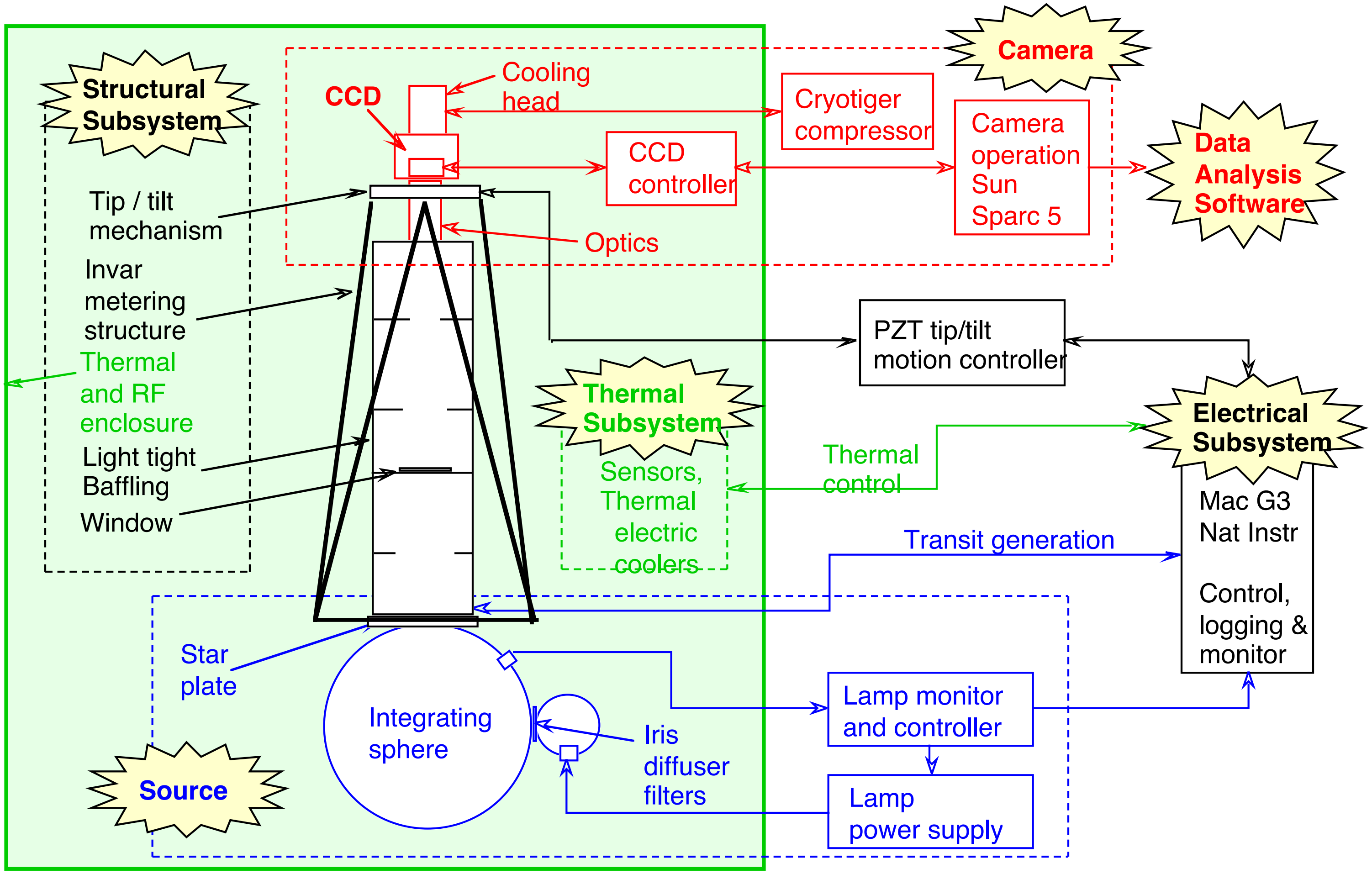
The Testbed Facility has been built to replicate the elements that will compose the flight system:

- A simulated star field that represents all of the features of the real sky that are important for ensemble photometry;
- A photometer that operates and has the same characteristics of the flight photometer, including:
  - Fast optics to focus the star field onto the CCD detector,
  - A commercially available CCD that could be used in the flight system,
  - High speed readout electronics (operating at 1 mega pixel/sec) to process the data as if onboard the spacecraft, and
  - Ground software used to produce the light curves, detect transits and evaluate the precision of the data;
- A structure that provides thermal, mechanical and RF isolation and stability from the laboratory environment.

The objective of the technical demonstration is to show that this end-to-end system can maintain the required relative precision over a period of time necessary to detect transits when all of the confounding noise factors are included. Note that the critical parameter is only relative precision, that is, the ratio of the flux of one star to the fluxes of many nearby stars read at the same time on the same CCD.

# Testbed Facility Description

- The **Source** simulates the sky and produces:
  - the same flux as for $m_V$=9-19 stars
  - a similar spectral color as the Sun
  - the same star density for $m_V$<19
  - several bright stars ($m_V$=4)
  - the ability to generate Earth-size transits




- The **Camera** simulates all of the functions of the Kepler photometer consisting of:
  - the fast optics, defocused images, CCD, CCD controller electronics, shutterless operation
  - control and data acquisition computer and software,
  - PZTs to simulate spacecraft jitter and a CCD cooling system.

The data are read out every 3 sec and co-added to form 15-minute integrations.

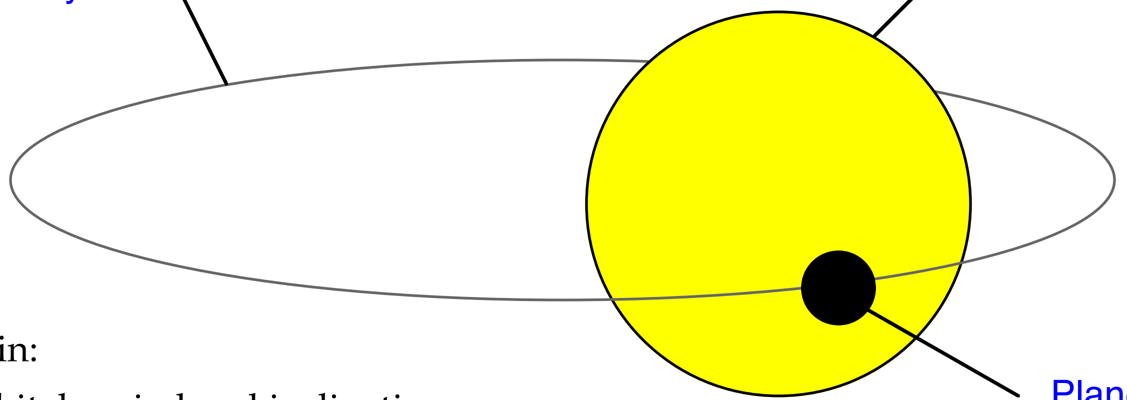
# TESTBED FACILITY CONSTRUCTION

Super-Invar metering truss on top of the base that houses the Labsphere integrating light source (seen in dark blue in the center photo.) Assembly began 55 working days after completion of the definition requirements for the facility.

Interior of the completed facility. The “gold” baffle sits on top of the star plate and extends to just below the camera optics. The top cylinder is the Cryotiger cooler and the next to top cylinder is the dewar housing the CCD. The interior aluminum walls are temperature regulated with thermal-electric-coolers/heaters.

The completed Test Facility at time of “first light”, 23 working days after beginning of the assembly.

# Information Obtained from Planetary Transits




From transit data obtain:

Duration, depth, orbital period and inclination.

Derive planet sizes and orbital radii (when combine with stellar information)

From ensemble of planetary systems:

Estimates frequency of planet formation for inner planets.

Distribution of planetary sizes, orbital sizes, coplanarity, effects of Jovian planets.

Additional science:

Expect 24 large planets in outer orbits (ground based follow up.)

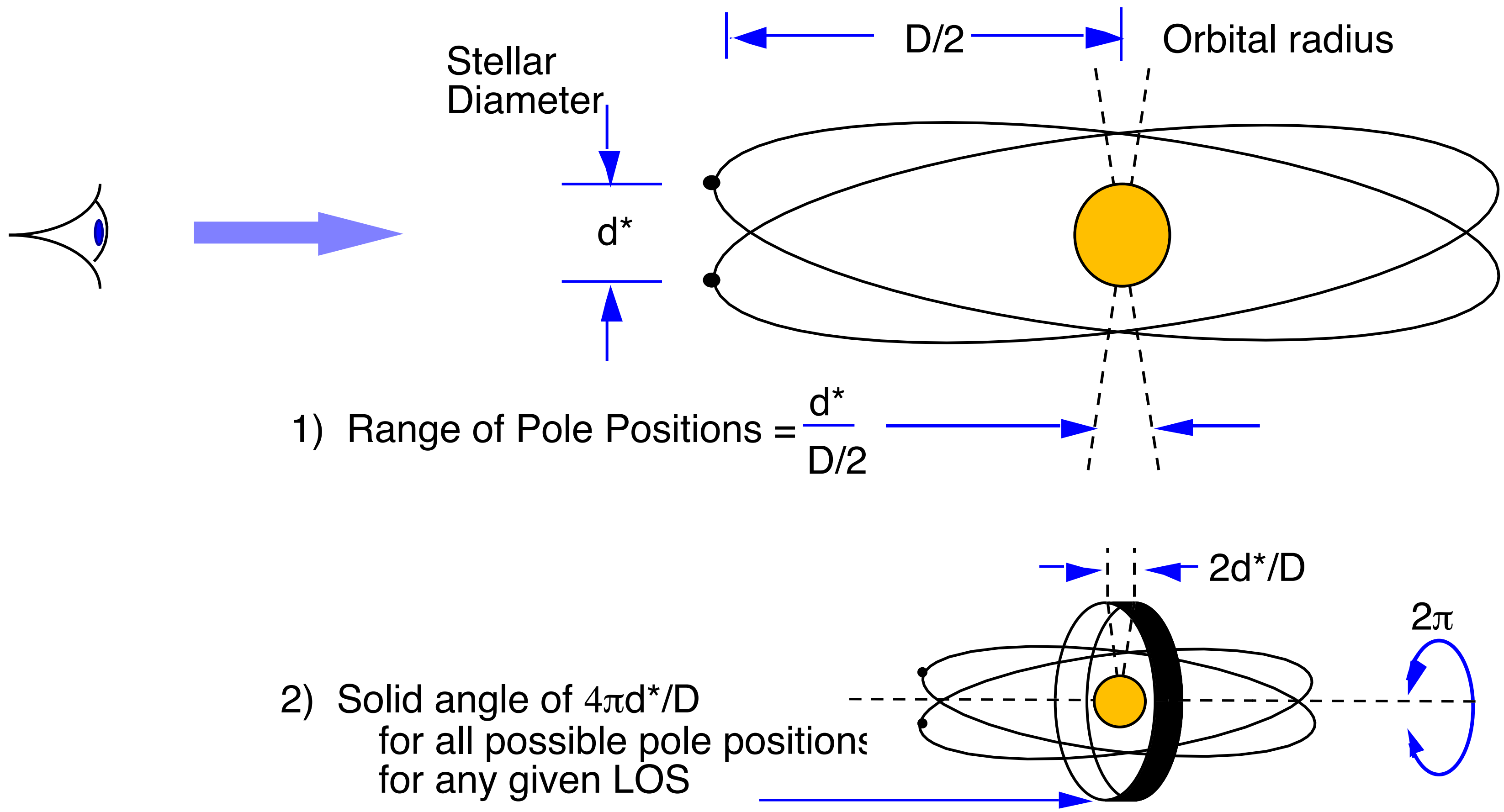
Stellar activity (star spot cycles, p-mode oscillations, white light flaring, etc.)

Frequency of Maunder minimums and the implications for the Sun and Earth’s climate.

Stellar rotation rates, limb darkening.

Extreme-mass-ratio eclipsing binaries.

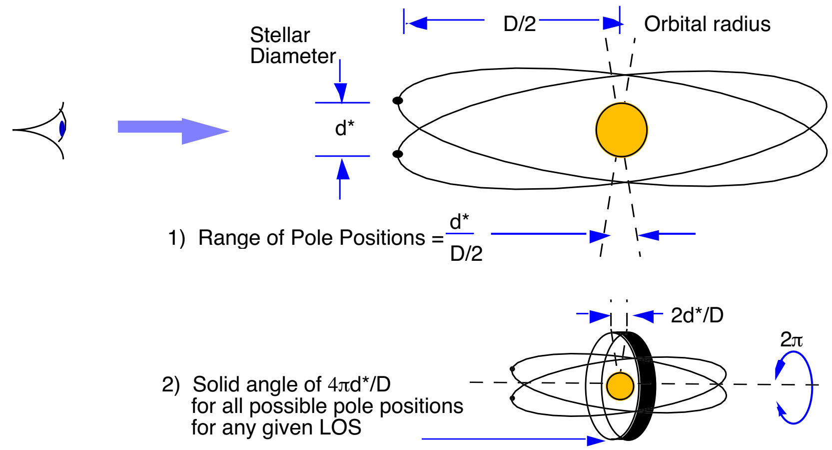
# Geometry for Transit Probability




**3) Geometric Transit Probability = d*/D**

# Geometry for Transit Probability

Transits are detectable when the planetary orbital pole is nearly perpendicular to the LOS, that is, within an angle of d*/(D/2), where d* is the stellar diameter and D/2 is the orbital radius. This is possible for all angles (2π) around the LOS, for a total of 4πd*/D steradians. Thus the random probability for seeing transits is simply d*/D.




**3) Geometric Transit Probability = d*/D**

If other planetary systems are similar to our Solar System with two Earth-class planets in inner orbits, then the geometric probability for seeing a transit is approximately 1%, since Earth-like and Venus-like transits have probabilities of 0.47% and 0.65% respectively.

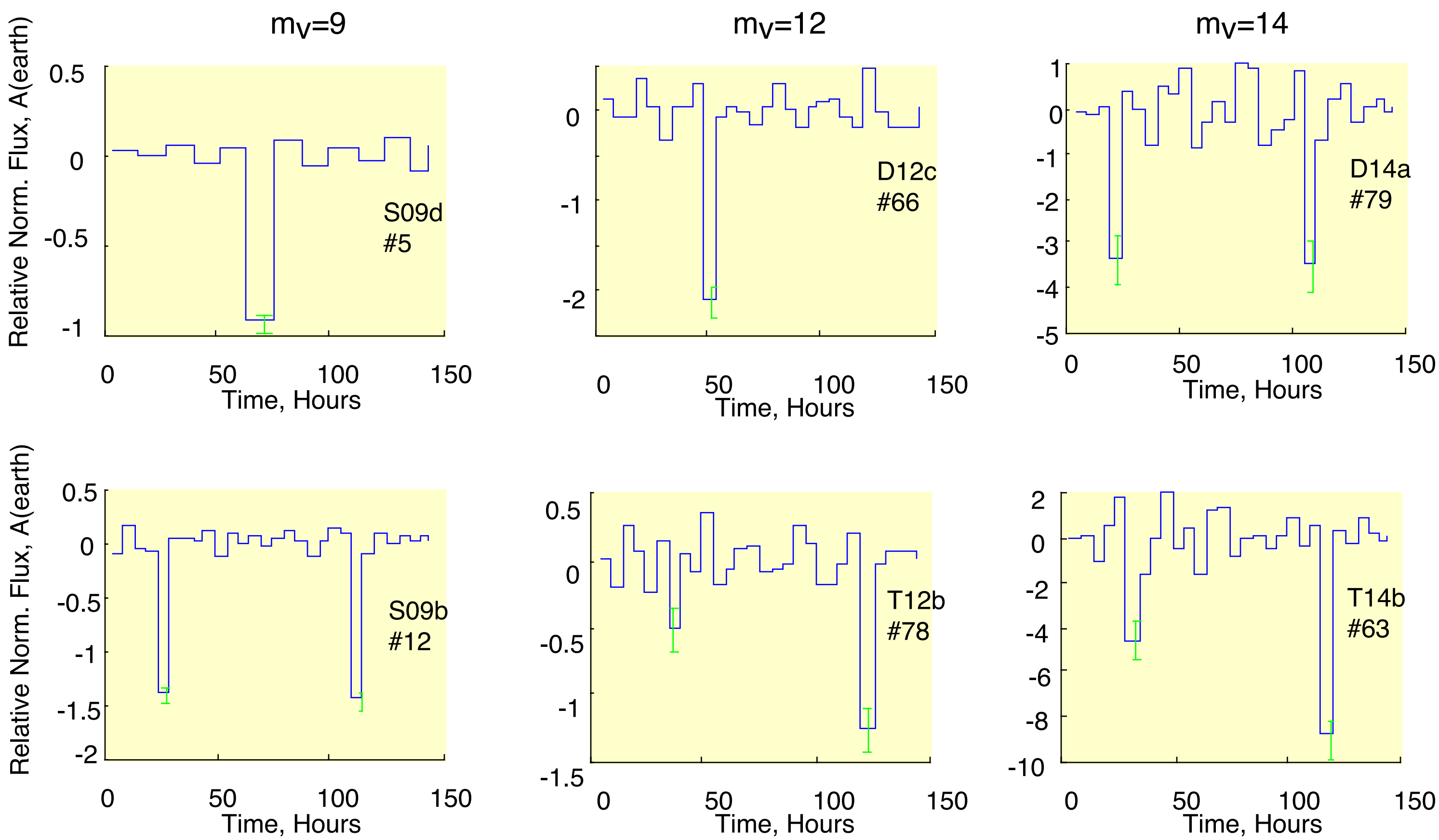
Also, if the orbits are nearly co-planar as in our Solar System then about 12% of the systems detected will show multiple planets.

# TRANSIT PROPERTIES FOR SOLAR SYSTEM OBJECTS

| Planet | Orbital Period P (yrs) | Semi-Major Axis R (A.U.) | Transit Duration (hours) | Transit Depth (%) | Geometric Probability (%) | Inclination Invariant Pl $\phi$ (deg) | Prob Sec Det (%) |
|---|---|---|---|---|---|---|---|
| Mercury | 0.241 | 0.39 | 8.1 | 0.0012 | 1.19 | 6.33 | 15 |
| Venus | 0.615 | 0.72 | 11.0 | 0.0076 | 0.65 | 2.16 | 23 |
| Earth | 1.00 | 1.00 | 13. | 0.0084 | 0.47 | 1.65 | 22 |
| Mars | 1.88 | 1.52 | 16 | 0.0024 | 0.31 | 1.71 | 14 |
| Jupiter | 11.86 | 5.2 | 30 | 1.01 | 0.089 | 0.39 | 18 |
| Saturn | 29.5 | 9.5 | 40 | 0.75 | 0.049 | 0.87 | 4 |
| Uranus | 84.0 | 19.2 | 57 | 0.135 | 0.024 | 1.09 | 2 |
| Neptune | 164.8 | 30.1 | 71 | 0.127 | 0.015 | 0.72 | 2 |
| Formulation | $P^2 M^* = R^3$ | | $13 d^* \sqrt{R/M^*}$ | $\Delta L/L = (d_p/\ d^*)^2$ | $d^*/\ D$ | $\phi$ | $\frac{4}{\pi\phi}\ \frac{d^*}{D}$ |

Note: $M^*$ is in solar masses; $d_p$ is the diameter of the planet.

# Transits for 9th, 12th and 14th Magnitude Stars




Transits produced and detected during the running of the long-duration test with all confounding factors. Transit depth is given in equivalent Earth-area and one sigma error bars are shown for the noise.

At 14th magnitude the minimum detectable planet size expected is 3.5 Earth-area due to a higher shot noise.